CRUISE REPORT

RRS *James Cook* cruise JC21

6th January – 10th February 2008

Rodman, Panama — Puerto Caldera, Costa Rica

"Accretion of the lower oceanic crust at fast-spreading ridges: a rock drill and near-bottom seafloor survey in support of IODP drilling in Hess Deep"

C.J. MacLeod (Chief Scientist)

D.A.H. Teagle, K.M. Gillis

P.W. Cazenave, H.E. Hansen, M. Harris, K.A. Howard, S.D. Hurst, B. Ildefonse, C.J. Lissenberg, A. Morris, D.J. Shillington & M. Tominaga

Isis Team: D.R. Turner, J.A. Cooper, S.E. Dodd, D. Edge, W.H. Handley, P.J. Mason, L. Rolley, A.M. Sherring
BGS Team: D.J. Smith, D. Baxter, N.C. Campbell, M.D. Wilson

School of Earth & Ocean Sciences,
Cardiff University,
Main Building, Park Place,
Cardiff CF10 3YE,
Wales, United Kingdom

CARDIFF UNIVERSITY
PRIFYSGOL CAERDYDD

CRUISE REPORT

RRS *James Cook* cruise JC21

6th January – 10th February 2008
Rodman, Panama — Puerto Caldera, Costa Rica

Contents

Cruise Summary

RRS *James Cook* Cruise JC21 (6th January–10th February 2008) investigated exposures of lower oceanic crust that crop out at Hess Deep (~2°15′N, 101°30′W); a rifted depression formed by the westward propagation of the Cocos-Nazca plate boundary towards the East Pacific Rise. Hess Deep provides unique exposures of the deeper levels of ocean crust formed at a fast spreading mid-ocean ridge, one of the fundamental processes in the solid Earth cycle. Our principal aims were to provide detailed site survey for future Integrated Ocean Drilling Program (IODP) drilling, and to collect a suite of deep crustal rocks with good geological context to test hypotheses of mid-ocean ridge accretion.

Our approach was: (i) to collect improved regional bathymetric (EM120), gravity and magnetic data using ship-mounted acquisition systems, then (ii) undertake detailed metre-scale bathymetry and near-bottom survey and sampling using the *Isis* remotely-operated vehicle (ROV), complemented by (ii) the drilling of shallow (~1m), geographically orientated cores using the 'BRIDGE' seabed rock drill. Twelve dives (*Isis* 67 to 78) were undertaken over an aggregate period of 14.5 days in depths from 3000 to 5400m, with different vehicle configurations for swath mapping and sample collection. Dives were typically ~36 hours duration, up to a maximum of 45 hours. Four dives (67, 68, 71, 74) collected high-resolution bathymetry using the *Isis*-mounted SM2000 multibeam echosounder. Driven at an altitude of 100m, with overlapping lines spaced between 150 to 200m, we obtained metre-scale bathymetry of 11km^2 from two areas: the slope north of the nadir of Hess Deep (~2°15′N 101°33′W; 5400 to 4400m), and the 'intra-rift ridge' horst block just farther north within the rift valley (~2°17.5′N101°32′W; 4200 to 3000m). Detailed maps generated onboard by the science party were then used to guide near-bottom geological mapping and sampling. Coupled with the surface data, these data provide new insights into the rifting history of Hess Deep. For eight dives *Isis* ROV was deployed near bottom to acquire digital imagery of basement exposures and to collect outcrop samples using the vehicle's manipulator arms. 145 samples totalling 760kg were collected, with the largest single dive haul being 157kg. Rock types range from harzburgite, dunite, troctolite, olivine gabbro and other gabbro lithologies, to dolerites and basalts. Our detailed mapping indicates a more complex distribution of rock types across Hess Deep than suggested by previous investigations, and requires significant refinement of presently accepted models for the structure and tectonic evolution of the rift. Importantly however, the ocean crustal stratigraphy at Hess Deep can still be re-constructed enabling primary science questions regading fast-spread lower crustal accretion mechanisms to be addressed in post-cruise study of the samples collected. The proposed IODP drilling (Proposal 551-Full5, Gillis et al.) will be enhanced and strengthened by our new findings with more confidently established geological context of potential drill sites.

The sampling of geographically oriented cores using the BRIDGE drill, required for determination of magmatic flow trajectories, proved challenging. This was principally due to the small size of (<10 m^2) outcrops, the rugged terrain and the great depth of operations (4800 to 5100m). Acoustic navigation of the drill using the ultra-short baseline (USBL) system was intermittent and imprecise at these depths, and high equatorial pelagic sedimentation rates commonly resulted in turbid near-bottom conditions that made precise positioning of the rig and site location difficult. Science operations at Hess Deep were interrupted to make a compassionate evacuation of a crew member in Costa Rica (24th to 31st January, 2008) reducing by more than a third the time available for science operations. This resulted in only one day being devoted to drilling, and only three BRIDGE drill deployments. These did not succeed in recovering orientated core. Because of the reduced science time available the second phase of science operations instead concentrated on the known rewards of ROV sampling. In consequence we did not have the opportunity to attempt to solve the difficulties of navigating the BRIDGE drill onto small outcrops in very deep water.

List of Participants

Science party (academic)

Dr Christopher J. MacLeod	*Principal Investigator/geologist*	*watch-leader 8-12*
Prof. Damon A.H. Teagle	*Co-Investigator/geologist*	*watch-leader 12-4*
Prof Kathryn M. Gillis	*Project Partner/geologist*	*watch-leader 4-8*
Dr Benoît Ildefonse	*Project Partner/geologist*	*8-12 watch*
Dr Antony Morris	*Recognised Researcher/geologist/geophysicist*	*8-12 watch*
Dr Donna J. Shillington	*Geophysicist/GMT team leader*	*8-12 watch*
Dr. Stephen D. Hurst	*Geophysicist/GMTer*	*12-4 watch*
Heidi E. Hansen	*Geologist*	*12-4 watch*
Michelle Harris	*Geologist*	*12-4 watch*
Dr C. Johan Lissenberg	*Geologist*	*4-8 watch*
Kerry Howard	*Geologist*	*4-8 watch*
Pierre W. Cazenave	*Computer Geek/GMTer*	*4-8 watch*
Masako Tominaga	*Geophysicist/GMTer*	*4-8 watch*

Science party (technical)

David R. Turner	*Isis team leader, National Marine Facility*
James A. Cooper	*Isis team, National Marine Facility*
Simon E. Dodd	*Isis team, National Marine Facility*
David Edge	*Isis team, National Marine Facility*
William H. Handley	*Isis team, National Marine Facility*
Peter J. Mason	*Isis team, National Marine Facility*
Leighton Rolley	*Computing technician/Isis team, National Marine Facility*
Alan M. Sherring	*Isis team, National Marine Facility*
David J. Smith	*BRIDGE drill team leader, British Geological Survey*
David Baxter	*BGS team, British Geological Survey*
Neil C. Campbell	*BGS team, British Geological Survey*
Michael D. Wilson	*BGS team, British Geological Survey*

Ship's crew

Antonio Gatti	*Master*		
Peter Reynolds	*Chief Officer*	Titus Owoso	*2nd Officer*
Darcy White	*3rd Officer*	Phil Harwood	*Purser*
Bernie McDonald	*Chief Engineer*	Glynn Collard	*2nd Engineer*
Chris Uttley	*3rd Engineer*	Bob Masters	*ETO*
Eamonn Ilett	*Sea Systems Manager*	Viv Wythe	*Deck Engineer*
Kevin Luckhurst	*CPO Deck*	Mark Squibb	*CPO Scientific*
Stuart Cook	*PO Deck*	Emlyn Williams	*ERPO*
Steven Duncan	*Seaman*	Martin McGeown	*Seaman*
Stephen Setters	*Seaman*	Colin Birtwhistle	*Seaman*
Mark Preston	*Head Chef*	Walter Link	*Chef*
Jacqueline Paterson*	*Stewardess*	Amy Whalen*	*Catering Assistant*
Graham Mingay#	*Steward*		

(**left ship, #joined ship – Puerto Caldera 27th January 2008*)

Academic science party contact details

Dr Christopher J. MacLeod	School of Earth & Ocean Sciences, Cardiff University, Main Building, Park Place, Cardiff CF10 3YE, Wales, UK Tel: +44-(0)29-2087-4332 Fax: +44-(0)29-2087-4326 E-mail: macleod@cardiff.ac.uk
Pierre Roger Cazenave	School of Ocean and Earth Science, National Oceanography Centre, University of Southampton, European Way, Southampton, SO14-3ZH, UK Southampton, SO14-3ZH, UK Tel: +44-(0)23-8059-3666 Fax: +44-(0)23-8059-3052 E-mail: pwc101@noc.soton.ac.uk
Prof Kathryn M. Gillis	School of Earth and Ocean Sciences, University of Victoria, P.O. Box 3500, Victoria, BC, Canada Tel: +1-250-472-4345 Fax: +1-250-6200 E-mail: kgillis@uvic.ca
Heidi E. Hansen	Department of Earth Sciences, University of Bergen, Allégt 41, N-5007 Bergen, Norway Tel: +47-90-87-04-50 Fax: +47-55-58-36-60 E-mail: heidi-elisabeth.hansen@geo.uib.no
Michelle Harris	School of Ocean and Earth Science, National Oceanography Centre, University of Southampton, European Way, Southampton, SO14-3ZH, UK Tel: +44-(0)23-8059-6133 Fax: +44-(0)23-8059-3052 E-mail: mh9@noc.soton.ac.uk
Kerry Howard	School of Earth & Ocean Sciences, Cardiff University, Main Building, Park Place, Cardiff CF10 3YE, Wales, UK Tel: +44-(0)29-2087-4830 Fax: +44-(0)29-2087-4326 E-mail: howardka@cardiff.ac.uk

Dr. Stephen D. Hurst
1301 W. Green St., 245 NHB
Urbana, IL 61801 USA
Tel: +1-217-333-0205
Fax: +1-217-244-4996
E-mail: shurst@uiuc.edu

Dr Benoît Ildefonse
Géosciences Montpellier, CNRS
Université Montpellier 2
34095 Montpellier cedex 05, France
Tel: +33-(0)4-67-14-38-18
Fax: +33-(0)4-67-14-36-03
E-mail: benoit.ildefonse@um2.fr

Dr C. Johan Lissenberg
School of Earth & Ocean Sciences,
Cardiff University,
Main Building, Park Place,
Cardiff CF10 3YE, Wales, UK
Tel: +44-(0)29-2087-4830
Fax: +44-(0)29-2087-4326
E-mail: lissenbergcj@cardiff.ac.uk
E-mail: jlissenberg@whoi.edu

Dr Antony Morris
School of Earth, Ocean and Environmental Sciences,
University of Plymouth,
Drake Circus, Plymouth PL4 8AA, UK
Tel: +44 1752 233120
Fax: +44 1752 233117
E-mail: amorris@plymouth.ac.uk

Dr Donna J. Shillington
Lamont Doherty Earth Observatory,
Columbia University,
61 Route 9W, Palisades, NY 10964, USA
Tel: +1 845-365-8818
E-mail: djs@ldeo.columbia.edu

Prof. Damon A.H. Teagle
School of Ocean and Earth Science,
National Oceanography Centre,
University of Southampton,
European Way, Southampton, SO14-3ZH, UK
Tel: +44-(0)23-8059-2723
Fax: +44-(0)23-8059-3052
E-mail: dat@noc.soton.ac.uk

Masako Tominaga
Department of Oceanography,
Texas A&M University,
3146 TAMU College Station, TX 77843-3146, USA
Tel: +1-979-204-2854
Fax:+1-979-845-6331
E-mail: masako@ocean.tamu.edu

Chapter 1. Introduction

1.1 Preamble

Royal Research Ship (RRS) *James Cook* cruise JC21 was funded by the UK's Natural Environment Research Council (NERC) via its programme of support for the Integrated Ocean Drilling Program (IODP). The UKIODP Site Survey Initiative (SSI) is a means to fund cruises that provide essential site survey information in support of IODP drilling proposals of high scientific interest and/or strategic value to the UK scientific community. One such proposal was ODP/IODP Proposal #551, by Gillis et al., which seeks to investigate the processes of accretion of the lower crust at fast-spreading mid-ocean ridges. This experiment proposed to drill a series of moderate depth holes (~300m) in the 'tectonic window' of lower crustal rocks known to be exposed in Hess Deep (2°N, 101°W), a rift valley lying at the intersection of the Pacific, Cocos and Nazca plates in the eastern Pacific Ocean. In part this proposal built upon the results of previous Ocean Drilling Program (ODP) operations there in 1992-93 (Leg 147). Kathy Gillis was a co-chief of this expedition and Chris MacLeod one of the scientific party. Although the follow-up ODP/IODP Proposal #551 included no British authors, its scientific themes and objectives are tightly aligned to the research interests of many UK scientists and institutions, including Chris MacLeod (Cardiff) and Damon Teagle (Southampton).

Proposal #551 was first submitted to the ODP in 1999. It was reviewed by the JOIDES Science Steering and Evaluation Panel, sent for external review, and then passed (with strong endorsement) to the Science Committee for potential scheduling. However, the Site Survey Panel (SSP) concluded that the available site survey data for Hess Deep was not sufficient for it to be considered for scheduling by the Science Committee. The proposal was therefore put aside until more detailed characterisation of the proposed drill sites was available. Thus it currently (in early 2008) remains, though now lodged with the successor to the ODP Science Committee, the IODP Science Planning Committee (SPC). If site survey information can be supplied, via the SSP, to the SPC, Proposal #551 may once again be considered for scientific ranking and potential scheduling at the SPC's March 2008 (and/or subsequent) meeting(s).

Efforts were made by the proponents of Proposal #551 to obtain site survey funding in the US and in Japan, but to date these have been unsuccessful. In 2003 Kathy Gillis agreed to a suggestion by Chris MacLeod that he attempt to obtain funding through the newly-announced UKIODP SSI. Following a pre-proposal in January 2004, full grant proposal NE/C509023/1 was submitted to the UKIODP SSI in April 2004. It was led by Chris MacLeod as Principal Investigator (PI) and Damon Teagle as Co-Investigator (Co-I), and included Kathy Gillis as a Project Partner. The other project partners were Benoît Ildefonse and Rolf Pedersen, both proponents of ODP/IODP Proposal #551, and Tony Morris was named as a Recognised Researcher.

Grant proposal NE/C509023/1 was approved for funding in mid-2004, and the wheels put in motion that were eventually to lead to the scheduling of cruise JC21 some three-and-a-half years later. One of the attractions to the reviewers of the grant application is that it proposed not only the acquisition of the requisite site survey data for ODP/IODP Proposal #551 but – with the plan to use the *Isis* remotely-operated vehicle (ROV) and British Geological Survey (BGS)'s 'BRIDGE' seabed rock drill to obtain large numbers of orientated samples from the Hess Deep lower crustal section – included an invaluable scientific programme in its own right.

1.2 Cruise objectives

The specific objectives of proposal NE/C509023/1 were as follows:

"(1) To find suitable locations for the drill sites proposed in the highly-ranked IODP proposal #551. This requires use of a remotely-operated vehicle or autonomous underwater vehicle to collect accurately navigated high-resolution bathymetry and seafloor photographs in order to identify areas of outcrop and/or flat benches suitable for spud-in by a non-riser drillship.

(2) To characterise the lithologies present at these potential sites, and provide geological context on a broader scale, by surveying and sampling in as much detail as possible the lower crustal section exposed on the southern slope of the intra-rift ridge of Hess Deep. This we intend to do by using the British Geological Survey's 'BRIDGE' seabed rock drill to collect geographically orientated core material, supplemented if appropriate with sampling using an ROV and/or dredging."

The broader scientific objectives were defined as follows:

"(3) To quantify as far as possible the heat and mass flux between mantle and crust and crust and ocean by constraining the structure, composition and alteration history of gabbroic rocks from the Hess Deep section.

(4) To test the hypothesis that the Oman ophiolite is an appropriate analogue for fast-spread ocean lithosphere.

(5) To test competing models for the accretion of the lower ocean crust at fast-spreading ridges."

1.3 Scientific background

A fundamental question in geodynamics is the nature of magmatic processes below oceanic ridges and, in particular, how the lower oceanic crust forms. Early, simple views involving single, large fractionating magma chambers in which the lower crustal gabbros accreted by side-wall crystallisation and crystal settling have now been largely abandoned. Seismic evidence from fast-spreading systems has identified a more restricted, perched magma lens at the top of the gabbro section which extends along the ridge, underlain by a broader zone of low seismic velocity that is inferred to represent a crystal mush containing a small but poorly constrained proportion of melt [e.g. Sinton & Detrick, 1992]. Slow-spreading axes ordinarily lack persistent magma bodies and the lower crust appears to freeze solid or nearly solid between melt delivery episodes from the mantle.

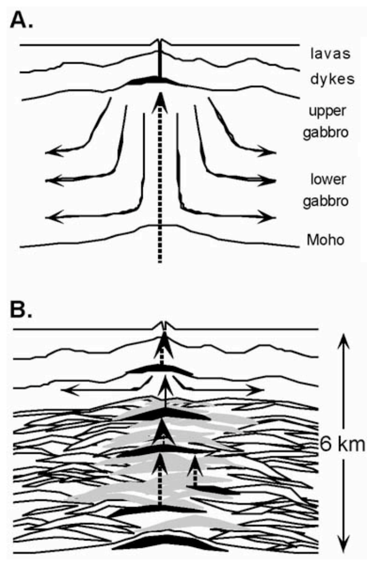

*Figure 1.1: **(A)** 'Gabbro glacier' vs **(B)** 'sheeted sill' models for accretion of the lower crust at fast-spreading ridges. Dashed arrows depict the direction of melt flow; solid arrows the flow direction of crystals. Sills which are melt-filled are shown in black, part-crystallised in grey, fully crystallised in white.*

These geophysical results have led to re-evaluation of the mechanism of accretion of lower crustal gabbros. Field evidence from the Oman ophiolite has been used to support the so-called 'gabbro glacier' hypothesis (Fig. 1.1) in which the gabbro section is built up by crystallisation along the floor and walls of the perched magma lens, followed by downwards ductile flow towards the Moho and away from the ridge [Henstock et al., 1993; Phipps Morgan & Chen, 1993; Quick & Denlinger, 1993]. This is opposed by a fundamentally different hypothesis, based upon the same field relationships in Oman, in which modally layered gabbros that form the lower part of the crust and Moho transition zone are suggested to form in situ in a series of 'sheeted sills', without any significant vertical transport [Boudier et al., 1996; Kelemen et al., 1997; MacLeod & Yaouancq, 2000] (Fig. 1.1). Magma ponded in such sills may crystallise 10-50% of their mass as cumulates (and develop compositional grading), with the remaining melt continuing upwards to form more evolved upper gabbros, dykes and lavas.

These models are all based upon the assumption that the internal structure of the Oman ophiolite is a direct analogue for modern fast-spread ocean lithosphere. The lower crust of the EPR should therefore be formed from gabbros that share the characteristic internal structure of the plutonic section in Oman: *viz.* a series of sub-horizontal layered gabbros overlain by more massive gabbros with steep, ridge-parallel magmatic foliations and lineations; and thence a thin layer of varitextured gabbros of heterogeneous texture and composition (Fig. 1.2). However, this is yet to be properly tested. Because of the inferred continuity of magmatic accretion at fast-spreading mid-ocean ridges the deeper levels of the crust are not normally exposed on the seafloor. This is marked contrast to slow-spreading ridges, where tectonic stretching is significant, and lower crust and mantle rocks are exhumed in many areas.

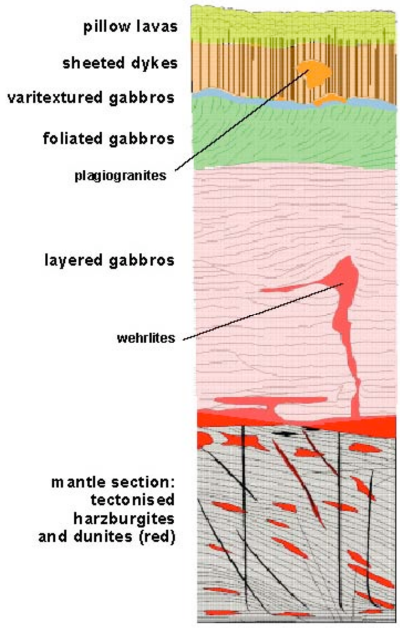

Figure 1.2. Internal structure of the Oman ophiolite [e.g. Nicolas et al., 2000].

Ocean drilling of intact fast-spread crust has so far penetrated only metres into plutonic rock, at ODP Hole 1256D [Wilson et al., 2006]. Until such time as we are prepared to commit the considerable resources needed to deepen this hole or drill another as far as the Moho, direct information as to the nature of processes beneath fast-spreading ridges, and testing of the Oman ophiolite analogy, is limited to exploring the very few 'tectonic windows' of fast-spread lower crust that are known to exist. Sections have been discovered at the margins of the three microplates that occur along the EPR: the Galapagos, Easter and Juan Fernandez microplates, found at 2°N, 23°S and 33°S respectively. The best known and most extensive of these is at Hess Deep, at the northern edge of the Galapagos microplate, and which has been the subject of previous submersible and ODP operations, detailed below. In many respects the gabbros drilled in Hess Deep do bear a close similarity to the foliated gabbros in Oman, and a marked dissimilarity to slow-spread gabbros [MacLeod et al., 1996a], but this is based upon very limited evidence, and the analogy needs to be explored far more rigorously.

1.4 Geology of Hess Deep: previous work

By far the most substantial and most accessible of the known tectonic windows of fast-spread lower crust is exposed in the Hess Deep rift valley (2°N, 101°W), near the Galapagos microplate at the Pacific-Cocos-Nazca triple junction (Fig. 1.3). The Cocos-Nazca spreading centre is propagating westward at a rate comparable to the half spreading rate of the EPR (~65 mm/yr); hence young (~1Ma) lithosphere generated at the EPR is being rifted ahead of the advancing Cocos-Nazca spreading ridge [Lonsdale, 1988]. Although this ridge-ridge-ridge triple junction is

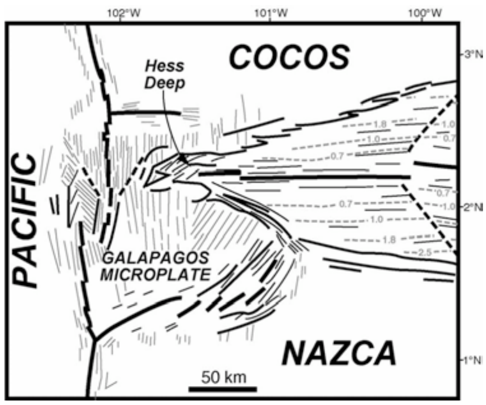

Figure 1.3. Location of Hess Deep at the Pacific-Cocos-Nazca triple junction

therefore stable on a regional scale, in detail the Galapagos microplate immediately south of Hess Deep appears to be rotating clockwise, and another tiny microplate to the north rotating anticlockwise, as the Cocos-Nazca rift propagates westward [Klein et al., 2005]. The EPR lithosphere that is entering Hess Deep has itself almost certainly been affected by earlier on-axis tectonics associated with long-lived duelling propagating rifts on the N-S EPR axis.

The principal topographic features of the Hess Deep rift valley are the Hess Deep nadir itself at 5400mbsl, the tip of the slow-spreading Cocos-Nazca ridge at 4000-4500mbsl, the intra-rift ridge that rises to 3000mbsl north of Hess Deep, and the steep bounding scarps north of the intra-rift ridge and south of the Hess Deep nadir (Fig. 1.4). Submersible studies [Francheteau et al., 1990] have shown that plutonic rocks are exposed on an intra-rift ridge and on the slope southward from it down to the axis of the Deep at ~5400 m water depth (Fig. 1.5). Minor outcrops of the uppermost gabbros are also exposed along the north wall of Hess Deep beneath extensive sheeted dyke and lava sections [Karson et al. 2002]. ODP operations during Leg 147 drilled a 150m-deep hole into gabbros on the western summit of the intra-rift ridge (Site 894) and two ~100m holes into harzburgites and dunites from the shallow mantle and inferred crust-mantle transition zone at the foot of the eastern end of the intra-rift ridge at Site 895 (Figs. 1.4 and 1.5; Gillis et al., 1993).

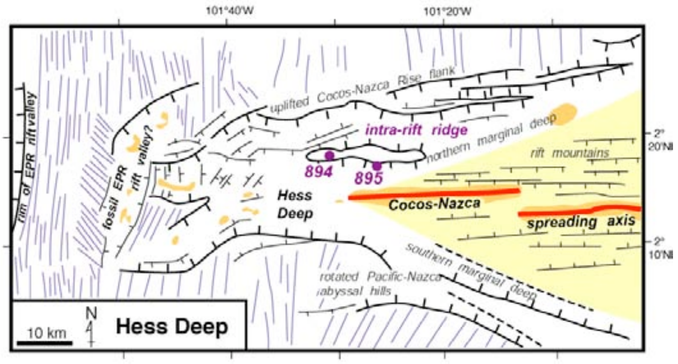

Figure 1.4. Tectonic elements of the Hess Deep rift valley

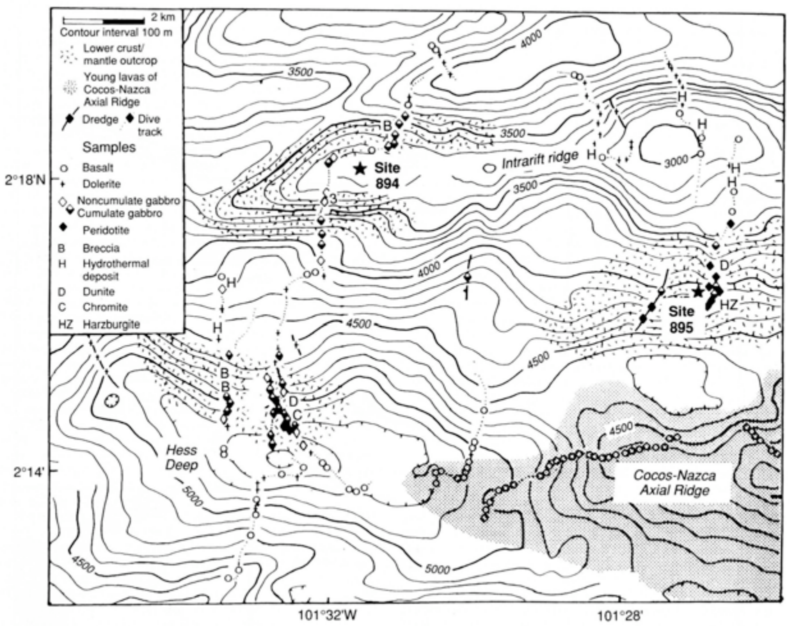

Figure 1.5. Location of Nautile *submersible dives and summary of lithologies recovered (Francheteau et al. [1990)] plus ODP Leg 147 drill sites (from Gillis et al. [1993])*

The tectonic disruption of the Hess Deep rift valley is complex and is not completely understood. Two models for extension and the emplacement of the intra-rift ridge were proposed by Francheteau et al. [1990]. One model invokes diapiric uplift of serpentinized mantle along high angle, normal faults. The other model calls for detachment faulting and block rotation on listric normal faults and diapiric uplift of the intra-rift ridge (Fig. 1.6). Structural and paleomagnetic data for Site 894 indicate that the intra-rift ridge represents a large, intact crustal block that has been rotated along both horizontal and vertical axes [MacLeod et al., 1996b]. MacLeod et al conclude that emplacement of the intra-rift ridge was accomplished by a combination of low-angle detachment and high-angle normal faulting (Fig. 1.7).

Geophysical surveys at Hess Deep provide support for the detachment model. On-bottom seismic data indicate low velocities (2-3 km/s) in the vicinity of Hess Deep with higher velocities beneath the intra-rift ridge (3.0-5 km/s) [Wiggins et al., 1996]. At Site 894, the

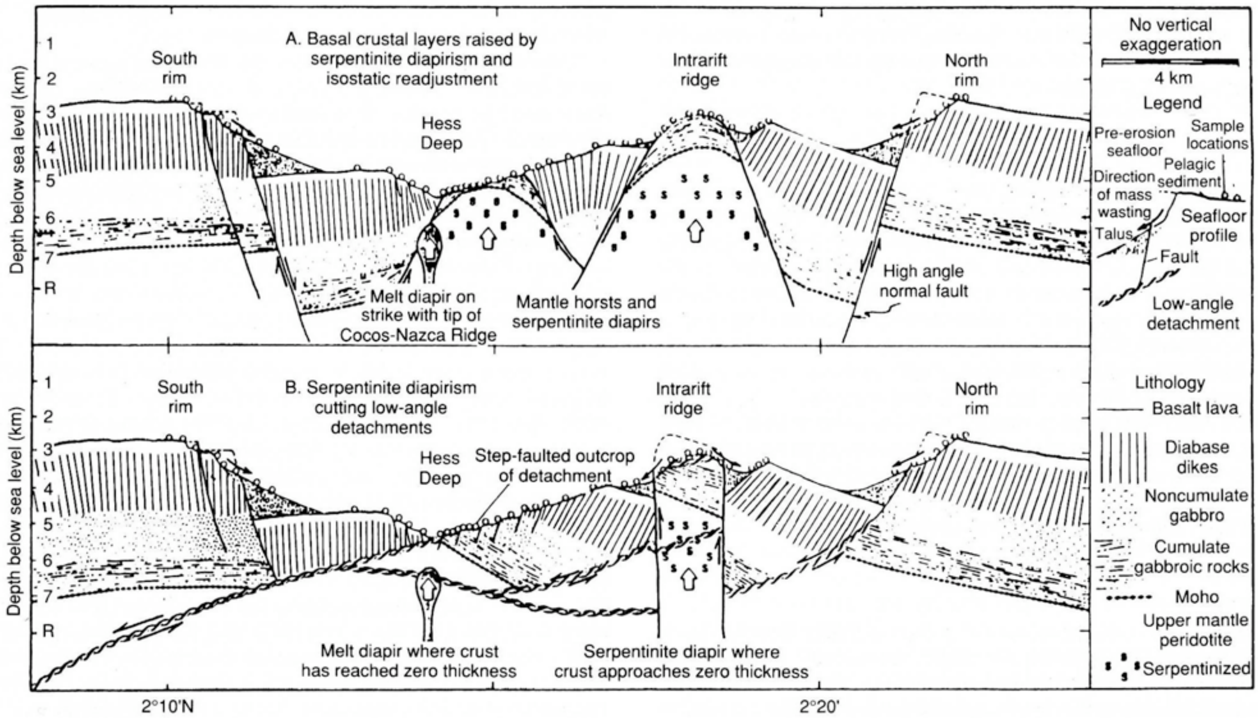

Figure 1.6. Two alternative models for the structure of Hess Deep, as proposed by Francheteau et al. *[1990]*

lowest seismic velocities occur within the upper 600 m where fractured gabbros crop out. Higher velocities with depth are interpreted as peridotite. Sea surface and seafloor gravity data indicate the presence of low density material beneath Hess Deep and high density material beneath the intra-rift ridge [Ballu et al., 1999].

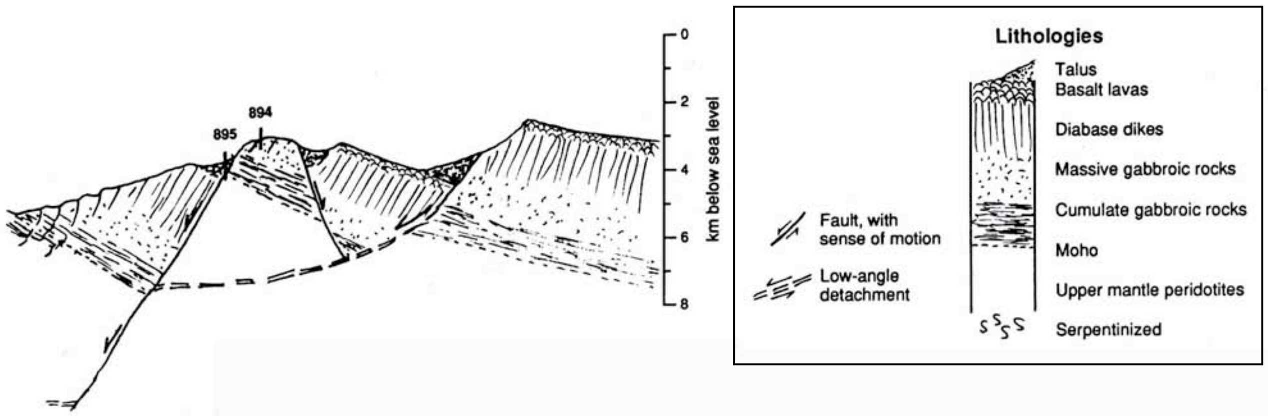

Figure 1.7. Cross section ththrough the northern part of Hess Deep as proposed by MacLeod et al. *[1996b] on the basis of drilling results from ODP Leg 147.*

1.5 Original survey plan

Prior to cruise JC21 the only geological information available to select drill sites for proposal #551 had come from two submersible dives by Francheteau et al. [1990]. Although these dives provide crucial reconnaissance on the distribution of outcrop and rock types there was limited coverage of the area of interest, and locations were sited using 1980s technology. The IODP Site Survey Panel therefore requested detailed, accurately navigated bathymetry and seafloor imagery to distinguish outcrop from talus, and find benches and other flatter regions into which non-riser IODP drill holes could be spudded in. Experience on Leg 147 showed that using a drill-string camera such as that on *JOIDES Resolution* is neither efficient nor reliable in finding good sites. The high-resolution bathymetry and seafloor images required therefore necessitated a near-bottom survey using an ROV. Our survey plan was to survey potential drill sites in the first instance using a swath mapping system mounted on the ROV and driven near-bottom (~100-200m altitude) to obtain high-resolution bathymetry of potential sites. The vehicle would then be deployed closer to the seafloor to obtain video imagery and photomosaics of the most promising areas. Sampling of the sites using the manipulator arms of the ROV and seabed rock drilling using the BRIDGE orientated coring device would characterise the local geology. Sample collection over the broader region would give broader scale context to the proposed IODP sites. In our original proposal we provisionally allocated 12 days to ROV operations, 2 days to on-bottom transponder deployment and/or contingency, and 10 days to the BRIDGE seabed rock drilling.

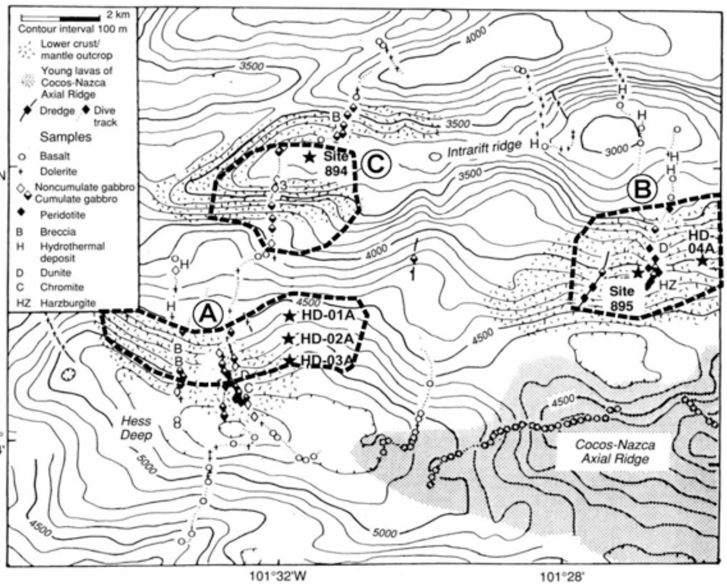

Figure 1.8. Survey areas provisionally identified in our original grant proposal. Area A was the main priority, followed by C and B as time permitted. Note that the locations of the proposed IODP sites HD-01A to -04A, taken from IODP Proposal #551, were slightly miscalculated, and were intended to lie along the Nautile *tracklines approximately 1.5km farther west.*

In Figure 1.8 we have indicated three areas of investigation, marked A, B and C, in which we proposed to survey and sample. Area A is approximately 18km^2 in area and includes the three proposed primary IODP drill sites (HD-01A to -03A) and the main area of lower crustal exposure proved by submersible investigation [Francheteau et al., 1990]. The three primary drill sites of Proposal #551 are located at 4400–4700 m water depth and it is planned that each IODP drill site would penetrate 100–300 m sub-surface. In a recent re-investigation of existing samples from Hess Deep [Coogan et al., 2002] found that the gabbros exposed here are very primitive compared to those from Site 894, and probably come from close to the base of the plutonic section. Peridotites are reported to be exposed below about 5000 m (Fig. 1.8; Francheteau et al. [1990]). Lower priority areas B (around Site 895 and backup site HD-04A) and C (summit and southern slope of the intra-rift ridge) are smaller and lie in shallower water (Fig. 1.8). For each area we planned in the first instance to conduct a deep-towed ROV bathymetry survey, running tracks with slight overlap between swaths parallel to the slope. In the original specifications of *Isis* (circulated in 2003-04, when the NERC proposal was written) it was stated that surveys of this kind could be carried out at 2km/hr (~1 knot) and that individual swaths up to 400m wide could be collected. It was estimated, therefore, that area A could be surveyed in about 30 hours and could be done in a single ROV dive. Subsequent practical experience in the months prior to and during cruise JC21, however, revised these estimates downward very significantly – to ~0.3kt towing speed and ~200m swath width. We consequently revised downwards our expectations of the area we could realistically swath-map during the cruise.

After the initial characterisation of the seafloor we proposed to spend more time conducting near-bottom photomosaic traverses up the slope over areas identified from the bathymetry as suitable drill sites, the aim being to find relatively flat benches of outcrop (or possibly flat sedimented areas) for the IODP sites and avoid talus ramps. We envisaged sampling the very steep buttresses of rock outcrop directly using the ROV. At the same time as surveying for potential IODP sites we would look for optimum sites for BRIDGE rock drilling. The amount of time we proposed to expend in areas B and C would depend upon the success of our investigations in area A, but at minimum we would conduct a survey in one of the other areas in order to find a suitable back-up site were area A found to be unsuitable.

In the original proposal we planned to use on-bottom long baseline transponder navigation in area A to ensure the most accurate positioning. However, prior to the cruise we established that it would be clearly advantageous to use the ultra-short baseline (USBL) navigation built in to *Isis* which, although it is slightly less precise, is significantly more reliable and does not necessitate the time-consuming deployment of an on-bottom transponder network. The USBL navigation provides horizontal accuracies of ~0.5% of water depth, i.e. ~±25m at 5000m. Because of the steep slopes and rugged crenulated topography of Hess Deep and short range of the NMF acoustic beacons, we would have had to redeploy the transponder network several times during the cruise (at 1-2 days per time) to survey the areas proposed.

Chapter 2. Ship's Systems

2.1 Description of ship-fitted systems

RRS *James Cook* is fitted with a number of deployment, instrumentation and data logging systems. Some of these systems are used to log data at all times whilst others are used during each cruise to achieve specific science objectives.

The "always on" systems include the Gravity meter, Surmet meteorological data acquisition, Applanix POSMV ship attitude and position systems, WAMOS wave radar, EA600 single beam echo sounder and the ships gyro which are all logged to Ifmersar Techsas data logging system. Also on board is a pCO2 system operated on behalf of PML which logs separately.

For cruise JC21 the equipment required for specific science objectives were the deep water multibeam echo sounder (EM120), Sub Bottom Profiler (SBP120), Sound Velocity Profiler (SVP) and (surface-towed) magnetometer. Available systems that were not used during JC21 were the EA500 single beam echo sounder, the EK60 "fish finder", ACDP and the XBT.

The deployment systems required for JC21 were the Deep Tow wire through the Starboard gantry for deployment of the BGS rock drill, the CTD wire through the starboard hydro-boom for deployment of the SVP and the Trawl wire through the Aft A frame for the rock dredge. The CLAM cable logging and monitoring system was used to log winch information to the Techsas system when in use.

Additional systems installed for the use of the scientific party include the V-sat satellite communications system along with the computer network and various public use computers and printers attached. Because of the failure of one of the main tracking boards within the V-sat system prior to the cruise, and our inability to source any spares at the time of the Panama portcall, the V-sat system was not available for use during JC21.

Sound velocity probe

Because the speed of sound in water varies depending on depth, temperature and salinity it is necessary to measure the sound velocity at each depth and produce a profile. The measurement of sound velocity is very difficult to achieve and so rather than measuring the speed directly the constituent parameters are measured and a calculation carried out within the device.

The output from the probe is therefore depth and sound velocity, which has been calculated from the readings of the pressure sensor, thermometer and conductance meter for the salinity.

For the hydrographic equipment to work as accurately as possible a sound velocity profile must be obtained in the area where the equipment will be used. For this purpose there are 2 SVP probes available on board the ship: an AML device and a Valeport.

The profiles used throughout the cruise were obtained using the Valeport probe deployed on the CTD wire through the starboard gantry. The probe is self logging and no data is available until the instrument is brought back on board and the log files downloaded from the device.

Upon reaching Hess Deep a SVP dip was carried out. Unfortunately as the winch system had not been used for a period of time several issues arose during this deployment.

During the first attempt one of the sheaves on the hydro-boom became very noisy at a depth of approximately 750m. As the depth of water at this location was 5000m the probe was retrieved due to the likelihood of permanent damage if the operation continued. The auto-greaser on the sheave was found to be faulty, causing the bearing of the sheave to be dry and causing the problem. The sheave was manually greased and the faulty auto-greaser replaced.

A second deployment was carried out, but when the probe was at approximately 1200m a joint in the hydraulic system supplying the winch room burst. This caused a loss of oil in the system and needed repair. The joint was repaired the oil also needed to be filled. All spilt oil was contained and disposed of correctly. The pipe work on board *James Cook* is poorly installed and as a result has put stresses into the system that periodically cause bursts of this nature.

This fault caused the probe to be stationary at 1200m for a period of 45 minutes after which the probe was taken to a depth of 4800m. When the probe was brought on board it was found that the data had stopped logging during the stationary period and a further dip was needed.

The third deployment was successful and the resultant sound velocity profile was imported into the EM120, SBP120, EA600 systems, and provided to the ROV team for use in their systems.

Kongsberg EM120 multibeam echosounder

The EM120 is used to perform seabed mapping to full ocean depth. The normal sonar operating frequency of the EM120 is 12 kHz with an angular coverage sector of up to 150° and 191 beams per ping. Achievable swath width on flat bottom will normally be 5 times the water depth. The EM120 transducers are linear arrays in a Mills cross configuration with separate units for transmit and receive.

The operator station for the EM120 is a computer in the Main Lab running Kongsberg Seafloor Information System (SIS) version 3.3 software on a Windows XP platform. There have previously been issues with disk space on the computer system, but since cruise JC15 additional hard drives have been installed and there were no problems with disk space during JC21.

Because of the depth of water at Hess Deep the EM120 was used for all ship swath operations, as the higher frequency EM710 system also fitted is only suitable for depth of less than 1000m. The EM120 was used extensively throughout the cruise both for preliminary swathing prior to ROV swaths and for opportunistic swathing during passages (see section 2.2 below).

Previously there have been problems using the EM120 at speeds above 4 knots, and even then the quality of the data has been questionable at higher sea states. This is a consequence of the precise position of the transducer array on the bottom of the ship and the cavitation caused by the bulbous bow. Fortunately during JC21 the sea was very calm throughout and good data were acquired, even at speeds of up to 12 knots. Ballasting the bow seems to improve data quality and this was done for the 12-hour swath survey conducted (at 4kt) when the ship first arrived at the survey area.

Position and attitude data is input to the hydrographic suite and then each of the echo sounders has offsets so that the depth data collected is referenced to its actual position on the seabed. Raw data from the swath system were passed to the scientific party who carried out post-processing on board (see section 2.2 below).

SBP120 sub-bottom profiler

The Kongsberg SBP120 sub-bottom profiler is an extension to RRS *James Cook*'s EM120 multibeam echo sounder. The EM120 receive-transducer hydrophone array used by the multibeam echo sounder is wideband, and by adding a separate low frequency SBP120 transmit transducer and appurtenant electronic cabinets and operator stations, the EM120 may be extended to include the sub-bottom profiling capability provided by the SBP120. The primary application of the SBP120 is to image sediment layers sub-surface.

Although not of prime importance to the scientific goals of the cruise, during JC21 it was turned on and logged while the ship was swath-mapping. The data were found to be unusable at speeds greater than 6kt and when using the ship's thrusters while on station. Logged SBP data files will be examined post-cruise to see whether any information of value to the goals of the cruise can be extracted from them.

At the beginning of the cruise there was a problem getting a reliable depth data input to the SBP120. This was traced to a problem on the Kongsberg network (the hydrographic suite has its own dedicated network) where the DNS server was not starting correctly and so the SBP could not get its depth data from the EM120. Once this was solved there were no further problems with the SBP.

Towed magnetometer

For this cruise a new Marine Magnetics SeaSPY magnetometer was installed temporarily on the ship. The computer in the Deck Lab was used as the deck unit and a cable run to the port aft quarter where the cable handling and deployment station was placed. The software provided with the unit is SeaLINK 8.0.

As this was a new installation there were inevitably some difficulties. In this case the main problem was in getting NMEA data into the computer so that it could be logged with the magnetometer readings rather than requiring that a cross reference to other files to get this data after the event. NMEA data, which includes the required GPS output, is broadcast on the ship's computer network. However the magnetometer software could not accept this input and required a serial input for this information. A small program was written which read the UDP broadcast data and output the data to a serial port, this output was then looped back into another serial port so that the magnetometer software could read it.

The magnetometer tow fish is deployed and recovered at a ship speed of 4 knots and needs to be at least 3 ship's lengths behind the ship to prevent any effect from the steel hull. The tow fish was therefore deployed to a position 280m behind the ship. This length plus the distance from the aft of the ship to the GPS antenna, 50m, is set as a "layback" distance in the software so that the data files contain positions of the tow fish rather than the ship.

The tow fish was deployed whenever the ship was swath surveying in the Hess Deep area: principally during the two occasions that we entered and left the survey area. Although it is not clear from the documentation what the maximum speed for use of the tow fish is, because the ship's opportunistic swath surveys later in the cruise were conducted at 10kt the tow fish was also used at 10 knots. The tension on the towing wire was checked and was not found to be excessive. It was also checked whether the fish was jerking or lifting out of the water. No problems were found and the magnetometer was used at this speed throughout.

Overall the magnetometer worked well and a permanent installation will be made following the end of cruise JC21.

Applanix POSMV

All positional and attitudinal data input into the scientific equipment onboard during JC21 received these data from the Applanix POSMV, either via NMEA strings distributed as UDP messages on the computer network or via serial RS232 cables.

The GPS antennae are mounted on the main mast and the gyro and attitudinal data are from a motion reference unit mounted at the xyz centre of the ship.

The pitch, roll and heading accuracy is specified as 0.02° (1 sigma). The positional accuracy is 0.5–2 m (1 sigma) depending on the differential corrections and the velocity accuracy is 0.03m/s horizontal.

Ultra-short baseline acoustic navigation (USBL)

For the purposes of tracking underwater beacons fitted to various pieces of equipment a Sonardyne USBL system is fitted to the ship. The deck unit is sited in the Main Lab and the detector head fitted to retractable poles which penetrate the ships hull at a point 13m aft of the centre reference point. The poles protrude approximately 2 m when deployed.

To allow the poles to be deployed there are sea valves to provide the openings and hydraulically operated rams which lower the poles with the sensor head attached.

There are two poles and two types of head fitted. The starboard pole has a standard head fitted. The port pole has a larger head which allows the transducers to be slightly further apart thus giving greater positional accuracy but sacrificing shallow water operation. In practice the shallow water capability does not seem to be affected when using either head.

Further information concerning the specifications of the system is not available on board ship and can be requested from NMF in Southampton post-cruise if required.

Gravity meter

A Model 'S' Air Sea Dynamic Gravity Meter System II was installed during the previous cruise and has been operating and logging since. During the port call in Antigua a base station tie-in was carried out and it is intended to carry out a further tie-in during the next port call which could be either Caldera, Costa Rica or Panama.

The Gravity meter is setup to log both locally and to broadcast data to the TECHSAS logging system.

The Model 'S' unit was in operation throughout the entire cruise. The machine requires very little in manpower overheads and only required checks to ensure correct operation in the morning and evening.

The specifications of the gravity meter are given below.

SPECIFICATION

SENSOR	
Range	12,000 mGal
Drift	3 mGal per month or less
Temperature Set point	46° to 55°
STABILISED PLATFORM	
Platform Pitch	±22 degrees
Platform Roll	±25 degrees
Platform period	4 to 4.5 minutes
Platform Damping	.707 of Critical
CONTROL SYSTEM	
Recording Rate	1 Hz
Serial Output	RS-232
Additional I/O	Ambient Temp, Sensor Temp, Sensor Pressure
SYSTEM PERFORMANCE	
Resolution	0.01 mGal
Static Repeatability	0.05 mGal
Accuracy at Sea	1.0 mGal
MISC	
Operating Temperature	0°c - 40°c
Storage Temperature	-30°c to 50°c
Dimensions	71 x 56 x 84 cm
Weight	Meter 86kg, Unit 30kg

2.2 Potential field measurements: operations

Gravity

Sea surface gravity field data were obtained with the Micro-g LaCoste Air-Sea Gravity Meter onboard and logged for the whole time the ship was in international waters. The gravimeter was mounted on a stabilised platform and corrected gravity field values for the effect of the pitch and roll of the ship (see section 2.1 above). Accuracy of the gravimetor operated at sea is typically 1 mGal or better. Collected data are raw regional gravity field (mGal) and Etövös correction (mGal) with 1Hz sampling frequency. Two types of .csv files (with extensions of .dat and .env respectively) are available for the gravity field data, ship attitude, and navigation. The raw gravity field as measured during the cruise ranges from 9190 – 9390 mGal through entire survey area. The gravity data will be corrected by tidal oscillation readings from Costa Rica and Panama ports. Free-air and Bouguer anomalies will be obtained from the sea surface gravity field data following successful application of these corrections and incorporation of navigation and of shipboard and near-bottom swath bathymetry data.

Sea-surface magnetics

Sea surface magnetic field data were obtained with Marine Magnetics SeaSpy Overhauser magnetometer (see section 2.1 above). The accuracy of this tool is stated at 0.001nT. It collects total sea surface magnetic field with 2Hz sampling frequency. It was towed 270m behind the port side of the ship, and deployed for those periods in which the ship was approaching or leaving the survey area, and during the brief swath survey conducted at the start of scientific operations. The raw magnetic field data range from 31200–32760nT through the survey area. In total four sea surface magnetic surveys were carried out:

Survey #1 (Julian day 013Z): The magnetometer was deployed underway during the ship swath bathymetry survey upon first arriving at Hess Deep. GPS was not acquired for the magnetometer location; hence the magnetic field data only have x-y-coordinates with respect to the ship's common reference point (GPS antenna). In general, a layback correction 45.7m astern of the antenna position needs to be added to the length of magnetometer cable is (x,y) = (0, 315.7). Data logging during this deploment often needed to be reset due to these issues, so the data sequence is more or less piecemeal and in need of a substantial amount of cleaning and concatenation along with the calculation of navigation data. The missing magnetometer coordination (latitude and longitude) will be re-calculated from the juxtaposition of the magnetometer with respect to the ship's GPS.

Survey #2 (024Z): The magnetometer was deployed underway from Station 11 to 12 during the ship swath bathymetry survey. The magnetometer was recorded with GPS data.

Survey #3 (031Z): The magnetometer was deployed underway from Station 12 to 13 during the ship swath bathymetry survey. The magnetometer was recorded with GPS data.

Survey #4 (038Z): The magnetometer was deployed underway from the Hess Deep to the final swath-mapped waypoint (2°31'N 100°36'W) upon leaving the survey area. The magnetometer was recorded with GPS data.

2.3 EM120 (ship's) swath bathymetry: operations and processing summary

Multibeam bathymetry data were acquired in Hess Deep upon arriving onsite (013Z), during most *Isis* operations, during a period of ROV downtime (024Z), and during transits to (024Z) and from Hess Deep to Costa Rica (031Z, 038Z) using the hull-mounted EM120 system on RRS *James Cook*. Very basic processing of these data resulted in a grid (100m x 100m spacing) of bathymetry data within Hess Deep and in surrounding areas to the SW, N and NE (Fig. 2.1). Additionally, the acquisition of bathymetry data during transits to and from Costa Rica also yielded swath coverage of the northern wall of Hess Deep at least as far east as 100°40'W. Combined with existing bathymetry data, these data cover most of the Hess Deep area (Fig. 2.2). New data provide higher-resolution images of well-studied parts of Hess Deep, including the nadir of the Deep itself, and the intra-rift ridge (existing datasets stored in the LDEO bathymetry database are gridded at 200 m). The survey lines to the southwest also show a northeast-southwest trending depression to

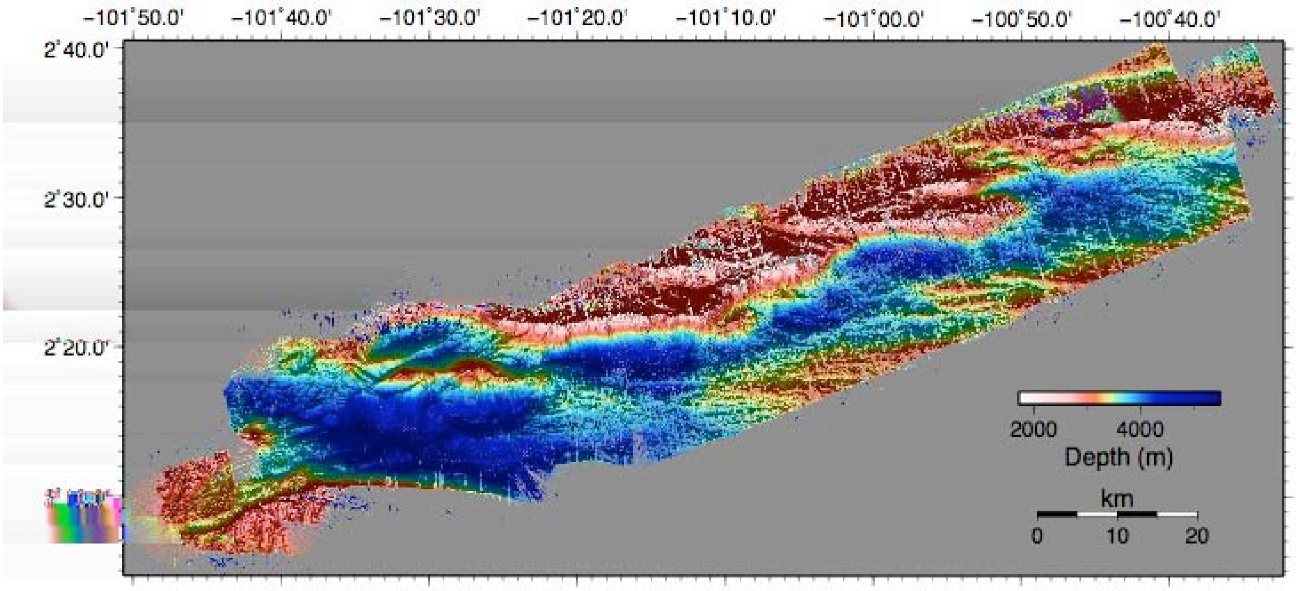

Figure 2.1. Bathymetry map of EM120 swath data collected during the whole of cruise JC21. The area shows the northern part of the Galapagos Gore, with Hess Deep at the WSW end of the area mapped (2°15'N, 101°30'W).

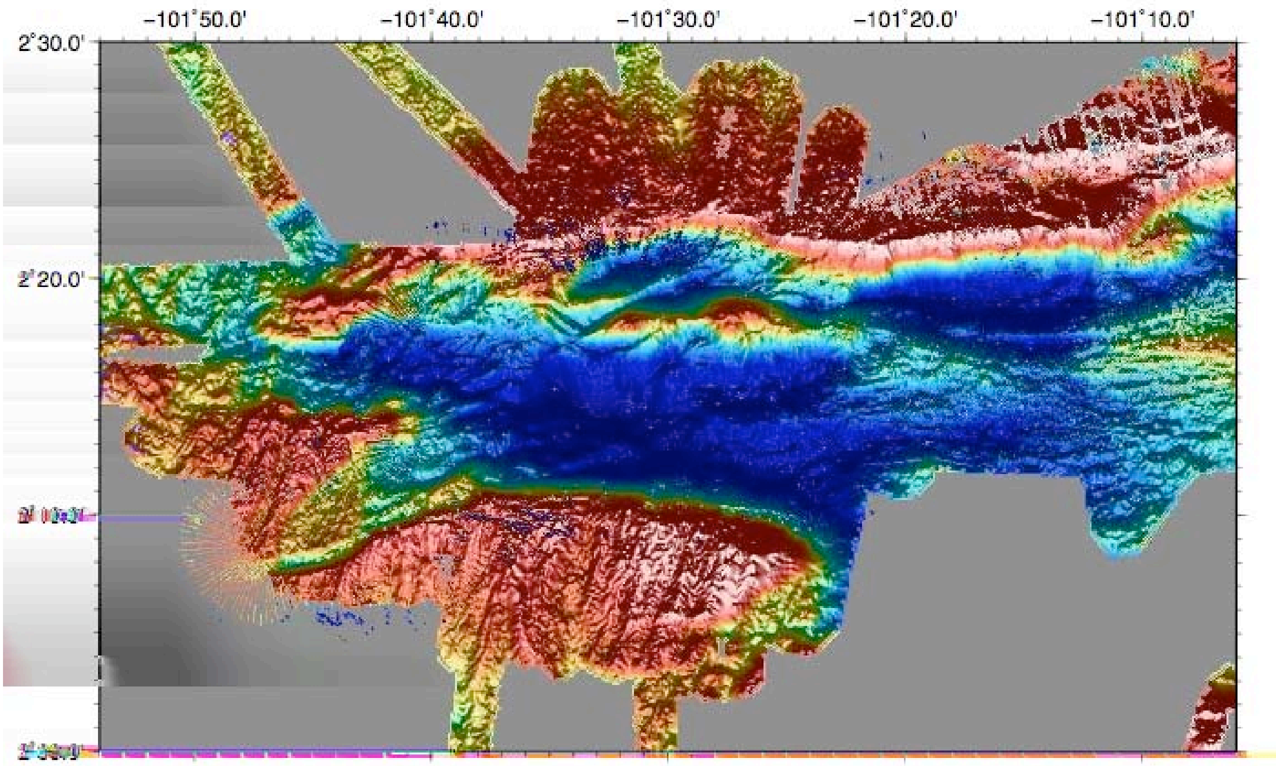

Figure 2.2. EM120 swath bathymetry map of Hess Deep, from data collected during cruise JC21.

the south of the main rift axis. Both NW-SE- and NE-SW-trending features can be observed within this depression. Swath lines collected to the NE of the main study area show a series of en echelon ESE-WSW trending ridges. Each ridge is approximately ~30 km long (E-W) and ~10 km wide (N-S).

Because of the limited processing applied to these data, they still contain noise, particularly at the outer parts of each swath. This noise is usually manifested as large negative spikes (i.e., deeper than surrounding seabed depth). There are also some bad pings, particularly in lines acquired at higher speeds: see section 2.1 above), which result in stripes of spurious returns perpendicular to the swath tracks.

Chapter 3. The *Isis* Remotely-Operated Vehicle

3.1 The *Isis* vehicle

Isis is a deep-diving ROV (Fig. 3.1) constructed for the UK marine science community by engineers at the Woods Hole Oceanographic Institution, USA. *Isis* was delivered in 2003 and is a near-identical clone of ROV *Jason 2* operated by WHOI for the US community. The vehicle is operated by Sea Systems, part of the NERC National Marine Facilities Division at the National Oceanography Centre, Southampton. ROV *Isis* has a depth rating of 6500m.

Figure 3.1. View of the forward part of the Isis vehicle, about to be launched from the port side of RRS James Cook. Note sample baskets on the sled, two manipulator arms, and array of forward-looking video and still cameras.

The vehicle frame is constructed from a combination of hollow and structural section aluminium, welded together to form a rigid structure. The frame is corrosion protected with anodes and ground-fault detectors. Nylon skids and 'D' rubber fenders protect the frame from impact damage during normal operations. Buoyancy is provided by syntactic foam modules (density 500kg/m^3) finished with elastomeric coating bolted directly onto the vehicle frame. Most electronics are housed in titanium pressure vessels with instruments connected to oil-filled electrical junction boxes via pressure balanced, oil-filled cable hoses. *Isis* has a large front retractable tray for the collection of scientific samples. Smaller swivel trays at the sides can carry additional samples. A maximum payload of ~150kg (weight in air) can be recovered. Propulsion is provided by six reversible 3.7kW thrusters, arranged with two thrusters each providing fore/aft, vertical, and lateral motion. The vehicle is controlled from the surface via a tether, with three optical fibres for data and three conductors at 3kV for power, linked to a modular control room with space for three operators/pilots and four or more scientists. This science control area includes equipment for event logging, video and data recording to a 7TB data store, record keeping and enables scientists to work directly with the pilots during survey and sampling operations. Detail of the video and still camera systems is given in Appendix A06. The information flow for *Isis* navigation, swath and other data is shown in Figure 3.2. In addition, the *Isis* package includes a two-container workshop with tools and spares, a winch and cable drum with 10km cable and an electro-hydraulic power unit for the winch and launching gantry. The package also includes eight guys who like to drink beer and chase girls.

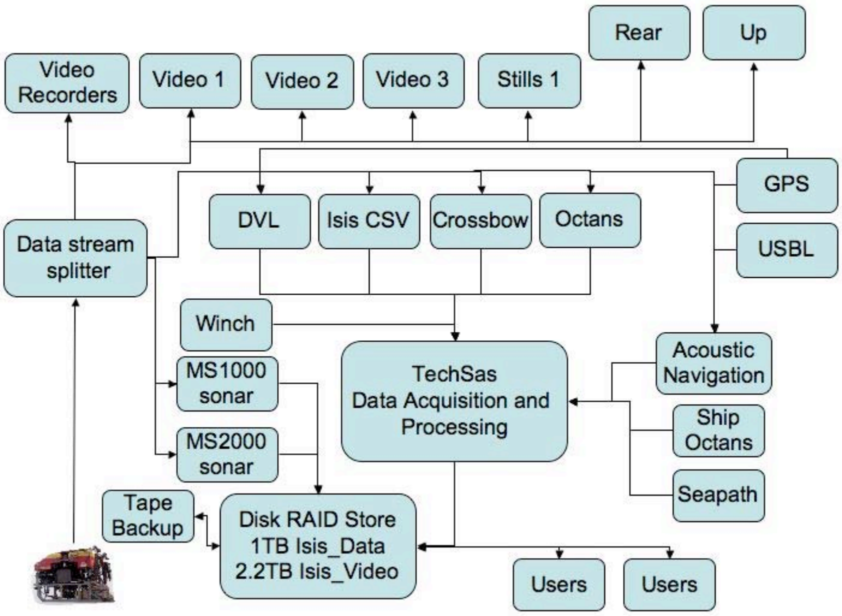

Figure 3.2. Isis information flow

Outline technical specifications for *Isis* are listed below:

- Length: 2.7 m; Width: 1.5 m; Height: 2.0 m; Weight: ~3T
- Max. working depth: 6500 m
- Max electric power 18 kW at 6500 m (~18kW lost in cable).
- Cable voltage: 3000V
- Maximum forward and lateral speed: $0.75 m.s^{-1}$ (1.5kt).
- Autopilot functions include:
  - Auto depth *(to $^+/_-$ 1m)*
  - Auto altitude *(to $^+/_-$ 1m)*
  - Auto heading *(to <$^+/_-$ 1°)*
- Hydraulic power unit 3.7kW for manipulators, trays etc.
- Power management between thrust, lights, hydraulics and user instruments to maximise use of power at depth.
- Forward tray and two side trays with hydraulic actuators.
- Quartz pressure transducer for depth with precision of <0.1%.
- Acoustic altimeter to give height off the sea bed when within 200m.
- Multi-channel serial, Ethernet and video communications over optical fibre.

Cameras and lights on Isis:

- Three Metal halide lights of 400W each provide the main forward lighting
- A 3-chip 850 line colour camera with a 14x zoom provides broadcast-quality video.
- A 3.34 Mpixel digital still camera with a 4x zoom for publication-quality pictures.
- Two standard resolution low light colour cameras with 12x zoom and pan and tilt control provide the pilot and scientists with their own general coverage video.
- Two red lasers mounted 10 cm apart allow picture scaling.
- Other video cameras monitor the tether and the rear of the vehicle.

Sonar systems on Isis

- SM2000 echo-sounder
- The MS1000 echosounder 675kHz single beam device

Hydraulic Manipulators: The "Predator"

- Base of Arm: *Pivot and swivel*
- Shoulder: *Pivot*
- Elbow: *Pivot*
- Wrist: *Pivot at 90°with continuous rotation*
- Claw: *Pinches, simple 'grab'.*

3.2 *Isis* operational strategy

The three main proposed sites of IODP Proposal #551 (HD-01A to -03A) are located on the south-dipping slope that rises to the north of the 5400m-deep nadir of Hess Deep, and thus formed the primary focus of our investigations (see section 1.5). This corresponds to area 'A' of Figure 1.8. Later in the cruise we also surveyed a smaller area on the southern flank of the intra-rift ridge: area 'C' of Figure 1.8. In each of these areas we first of all employed the ROV to acquire high-resolution swath bathymetry (section 3.3), and then conducted near-bottom operations to sample the sections just surveyed.

Swath surveying of area A was done on *Isis* dives 67, 68 and 71, and of area C on dive 74. Near-bottom sampling of area A was undertaken on dives 69, 70, 72 and 73. Area C was sampled during dives 75 and 76. Near-bottom dive 78 was made on the northern part of the summit of the intra-rift ridge, and relied upon the much lower resolution EM120 swath bathymetry to guide navigation and sampling, as was dive 77, which was located on the narrow saddle at the centre of the intra-rift ridge. Track lines for these dives are shown in Figures 3.3 and 3.4.

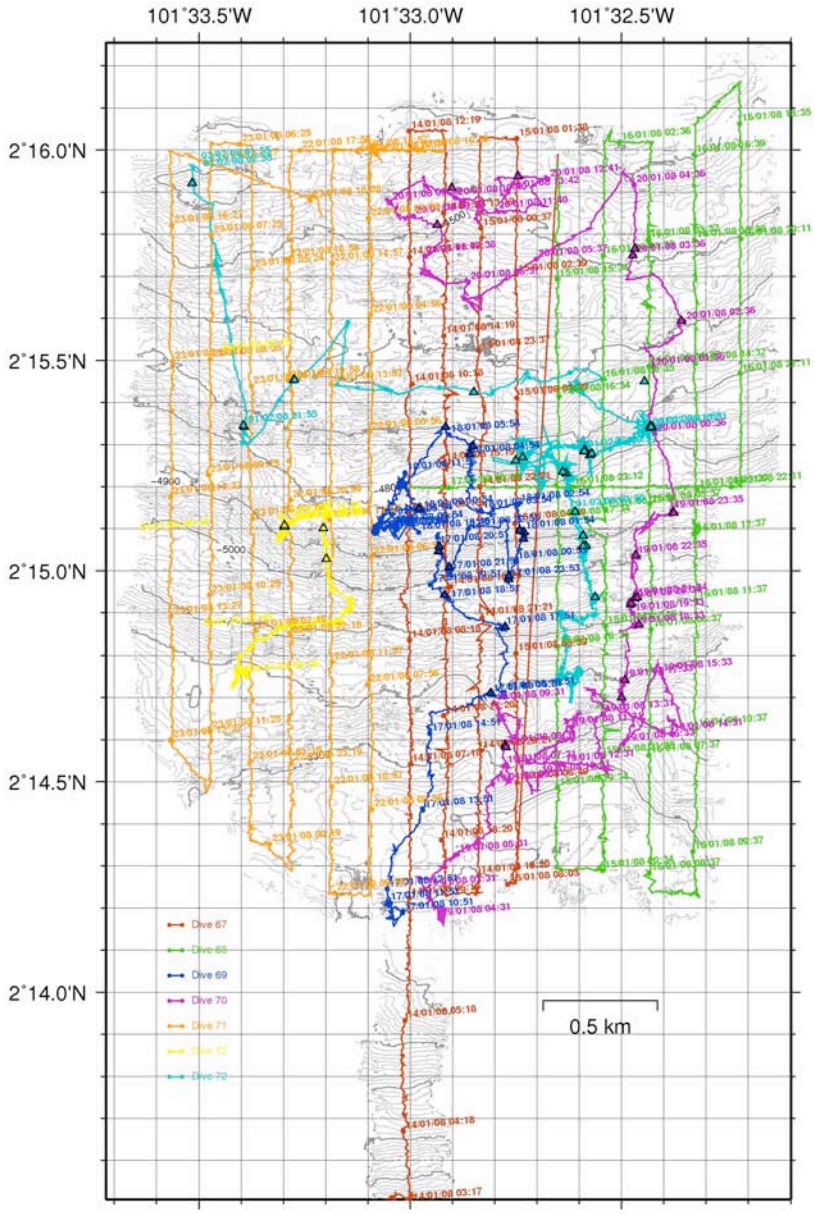

Figure 3.3. Isis dives in area A.

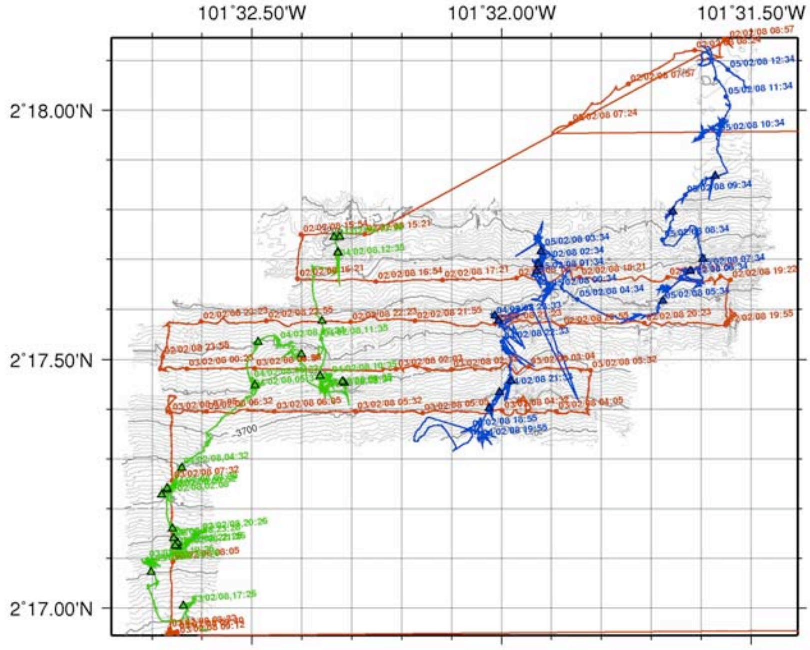

Figure 3.4. Isis dives in area C.

3.3 *Isis* swath acquisition and processing

The bathymetry surveys of *Isis* dives 67, 68, 71 and 74 used the Kongsberg SM2000 sonar swath bathymetry system mounted on the vehicle to produce high-resolution bathymetric maps of the seafloor. The SM2000 system emits 128 ultrasonic beams over a swath of 120° perpendicular to the *Isis* ROV heading. The system receives reflected returns from each beam and calculates the range, direction and intensity of the sonar returns. This information is displayed in real-time in the ROV control vans for watchstanders (Fig. 3.5). Meanwhile, ship and ROV navigation and ROV pitch, roll, yaw and depth data are also collected.

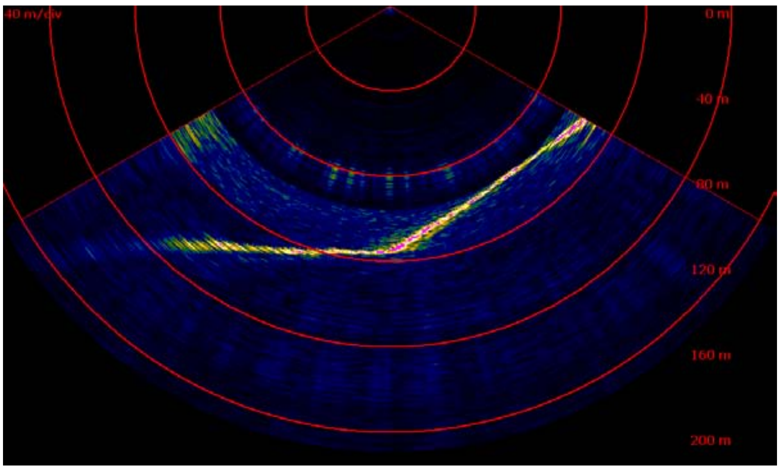

Figure 3.5. Screenshot of MS2000 acquisition software showing raw sonar returns from one ping. Depths are autopicked. Note the poor return from the left-hand extremity of the scan; no depth data would be picked from here. Instead, the system may pick spurious returns from the higher-amplitude noise at far left.

Dives 67, 68 and 71 were run in a N-S direction, up and down the slope of area A. Dive 74, on the southern flank of the intra-rift ridge, was run E-W, in part to minimise the amount of time lost in turning the vehicle. Brief crossing lines were run for each dive to assess inter-swath errors; typically differences were found to be no more than 1-2m between adjacent swaths. This is most likely due to an uncorrected static pitch error. These will be removed by further processing post-cruise (see below).

For each of the mapping dives *Isis* was towed at 100m altitude, the optimum depth determined both for data quality and swath width on our Coiba Ridge test deployment (dive 66) during our transit at the start of the cruise (see Chapter 6 and

Appendices A05 and A06). Swath widths for the N-S transects varied from ~70m up to 300m, though a 200m wide swath of useable data was typical (i.e. 2 x towing altitude). For the E-W transects it was slightly less – typically 175m – and asymmetric with respect to the vehicle position (much narrower up-slope). Data from the E-W transects were, however, less noisy than for the N-S lines, probably because the vehicle was more stable and easier to fly. The spacing of swath lines was 150-200m.

The acquisition software for the SM2000 sonar is the Kongsberg MS2000 software package. The Caraïbes data processing system takes input from the MS2000, together with the navigation and ROV attitude data, and merges it with the sonar range and direction data to produce xyz coordinate data. This system is also used to clean and smooth navigation data and to remove noise and other 'inappropriate' sonar returns from the data set. Smoothed USBL navigation was used for all onboard bathymetry processing because Doppler navigation files could not be read by the Caraïbes software. This produced accurate swath positioning accurate to within approximately 10m after significant smoothing, but errors much greater than the nominal 25m expected from USBL specifications on short time scales. In principle, Caraïbes is supposed to correct the bathymetry data for attitude variations, but significant roll artefacts are still apparent perpendicular to the line direction. These artefacts degrade vertical resolution as much as 5-10m at the edges of swaths, and will need to be removed post-cruise. We also noticed a 1-2m systematic depth variation that varies with *Isis* track direction when going upslope or downslope. This is most likely due to an uncorrected static pitch error. Finally, high-amplitude instrument generated noise during swath acquisition resulted in a large number of bad picks of seabed reflection, requiring significant data cleaning; ~18% of data points were removed during this process. The cleaned bathymetry data is merged with smoothed navigation and gridded with a spacing of 4m to produce the final bathymetry maps shown in Figures 3.6 and 3.7.

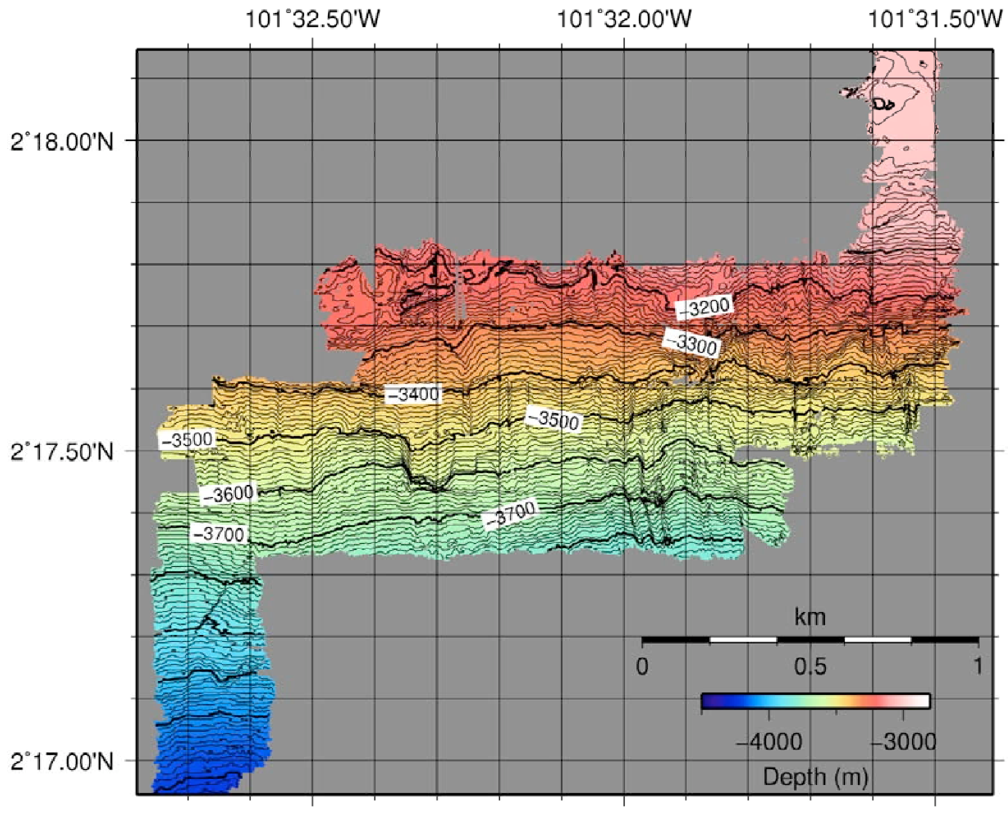

Figure 3.7. SM2000 bathymetry map of area C (southern slopes of the intra-rift ridge).

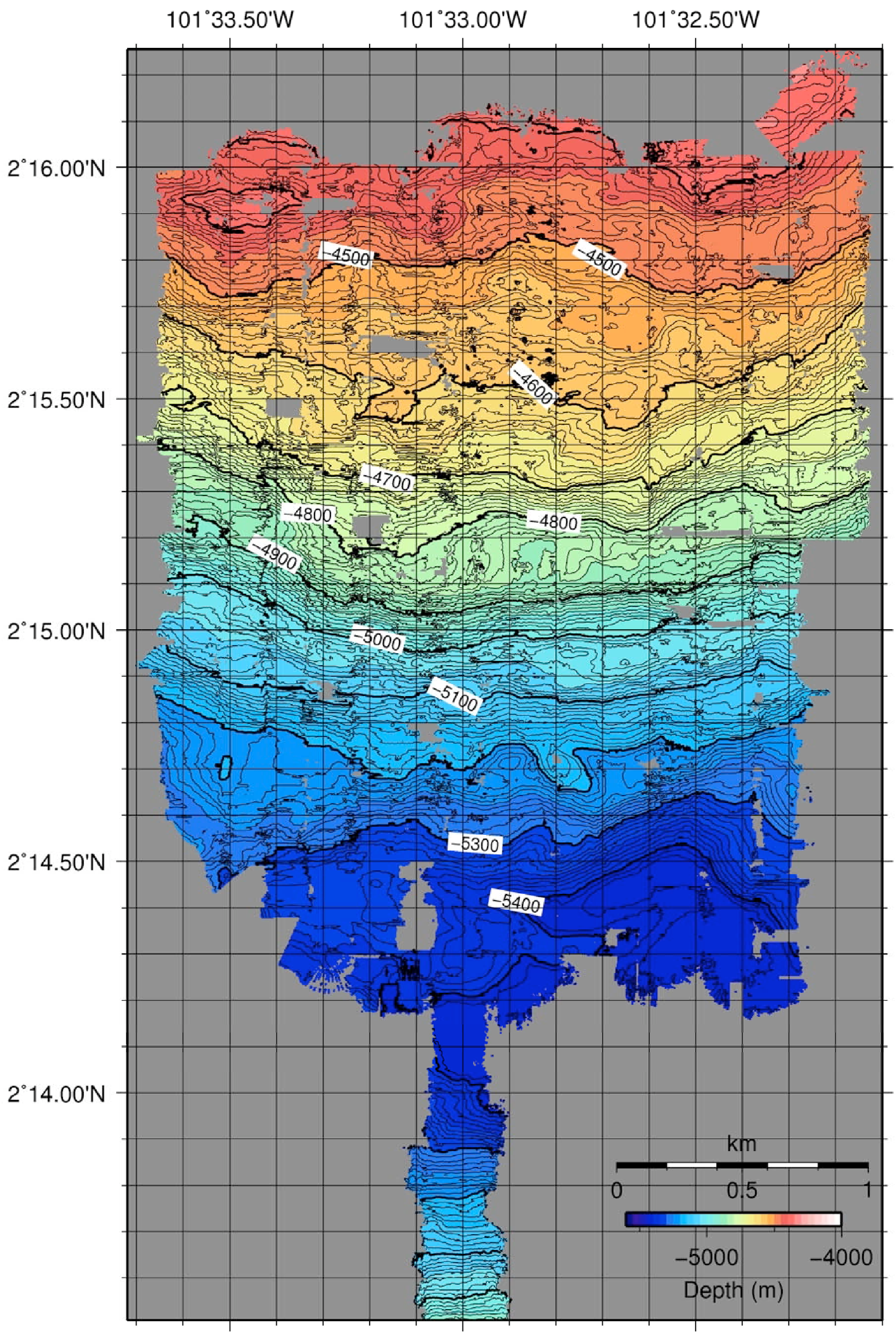

Figure 3.8. SM2000 bathymetry map of area A (slope north of Hess Deep nadir).

Area A (2°13.5′N to 2°16.2′N latitude, 101°32.1′W to 101° 33.65′W longitude)

Area A (Fig. 3.8) mainly stretches from the nadir of the Hess Deep Rift at 5482m below sea level to the north at a contour level of 4400m. The bathymetry of this area essentially trends monotonically from the deepest point in the south to the highest level in the north and contours generally follow E-W orientations. At a slightly greater level of detail the contours are slightly concave to the north, so that areas directly east or west from the centre of the swathed area tend to be at greater depths below sea level. The average slope from the deepest spot to the top of the area is 18°. We initiated mapping in Area A with a single swath that commenced on the north-facing slope south of the nadir of Hess Deep (Fig. 3.8). This area is not otherwise described here because no other work was performed in that section.

The gross structures in the ~3 x 3km area are a series of relatively flat benches and steeper slopes that generally trend E-W and thus correspond to contour levels. The benches roughly occur over 5300 to 5200m, 5100 to 5000m, 4900 to 4800m, and 4750 to 4550m, with the steeper slopes above and below. Particularly steep areas that proved fertile for outcrop and sampling were between 5000 to 4850m on the west side of the area and the equivalent slope between 4950 and 4860m in the eastern half. Another productive steeply dipping area was between depths of 4820 and 4700m across the whole width of the mapped area.

The section of the area shallower than 4700m had overall gentler slopes and includes flat protrusions to the south at 101°32.15′W and 101°32.65′ around the 4600-4700 m level. There is a local high approximately 100m above surrounding terrain in the NW corner of the area. Maximum gradient maps and angled illumination maps (Appendix A03) show both the flatter benches and steeper areas described.

Second-order features of the area include a set of ridges and valleys from NE to SW making up spaced lineaments, especially pronounced in the eastern half of the area. These cut the benches and overall E-W trend of the contours but are evident in the angled illumination maps and the 3-D visualisation of the bathymetry. Of particular interest, because of subsequent intensive rock sampling, is the lineament trending from 2°15.2′N 101°32.8′W to 2°15.65′N 101°32.2′W. Other parallel lineaments are spaced 200-400m to either side.

Area C (2°16.95′N to 2°18.15′N latitude, 101°32.8′W to 101°31.45′W longitude)

Area C (Fig. 3.7) consists mainly of the upper portion of the steep slope to the south of the western part of the intra-rift ridge. Again, the bathymetry of this area essentially trends monotonically up from the deepest point in the south to the highest level in the north and contours generally follow E-W orientations. Single N-S trending swaths were added to a generally E-W elongate area at the SW and NE corners of the overall area. Coverage is predominately in the middle third of the rectangular area defined above. The main area covered with five E-W adjacent lines is 2000m E to W and 850m from N to S. Average slope from the deepest spot to the top of the area is 35°, with the steepest slopes in the middle of the swathed area.

The major bathymetric features of Area C are significant N-S trending ridges with adjacent valleys and chutes that occur at: 101°31.6′W from 3100 to 3300m; 101°31.54′W from 3400 to 3500m; 101°31.87′W from 3200 to 3400m; 101°32′W from 3350 to 3800m; and 101°32.35′W from 3500 to 3650m. In addition, there is a long ridge trending 030° in the SW corner of the area that has a more subtle bathymetric expression, but was followed and sampled for over 500m horizontally and 300m vertically during *Isis* dive 75 (Fig. 3.7).

3.4 Use of a deep-towed magnetometer on *Isis*

In addition to the measurements made using the towed shipboard magnetometer (section 2.1), magnetic field data were also obtained using a vector three-axis Honeywell HMR2300 Magnetoresistor magnetometer housed on *Isis*. This was lent to us by Maurice Tivey (WHOI). For each dive, *Isis* carried out a calibration turn during the descent of the vehicle prior to the survey. The calibration data can then be used to correct the measured magnetic field for the effects of the vehicle. Of the twelve *Isis* dives in the survey area, data were collected for all but dive 68, for which the instrument had been removed because of a cable problem on the preceding dive. On dive 73 magnetometer data for the first 20 hours of the survey were not recorded because of a data logging problem. Detailed summaries of operations are described in Appendix A02.

All data were merged and processed based on the time-based data sequences, including magnetic field measurements, navigation, and vehicle attitude data. The data decoding and sorting were done using perl scripts written onboard to construct proper format file for the calibration calculation on MATLAB programs authored by Maurice Tivey. The details of the onboard data processing, mainly about the calibration calculation processes, together with the scripts for decoding *Isis* magnetic data to carry out this calculation processes are provided in Appendix A02.

With successful calibration of the magnetic data, post-cruise magnetic data analyses can be done to obtain regional magnetic anomaly information. These analyses will include corrections of: along-track bathymetry, slope (tilt) angle, diurnal effects with data from terrestrial base station, and IGRF. It should be noted that diurnal correction is particularly important for high resolution magnetic analyses around the equatorial area. This is because the ionization of ionosphere by sun during daytime results in large DC offset in the Earth's geomagnetic field, which is approximately ± 50 nT. The inversion and forward calculations will be carried out to produce grid map of anomaly and magnetization distribution. The Gaussian deconvolution routine will contribute to detect the three dimensional distribution of these parameters.

3.5 *Isis* near-bottom operations

The swath bathymetry mapping described in sections 3.2 and 3.3 formed the basis for a detailed near-bottom sampling programme using *Isis*. The configuration of the vehicle was changed by removing the SM2000 multibeam sonar array and other non-essential items in order to maximise the payload of rocks. Baskets with 6-8 slots marked with unique identifier codes were constructed for us by the *Isis* team and these were mounted on the vehicle sled (Fig. 3.1).

Dives 69 and 70 sampled the areas swath mapped in dives 67 and 68 respectively. Dive 72 started to sample along the area of swath dive 71, but had to be aborted for us to make the emergency transit to Costa Rica on 24th January (see Chapter 6). Dive 73, the first after returning from Costa Rica on 31st January, sampled in greater detail between dives 69 and 70, and then completed the upper part of the dive 71 swath area (the NW corner of area A). Dives 75, 76 and 78 were located on the western part of the intra-rift ridge, and dive 77 on the central saddle.

Dive tracks, together with a summary of the lithology of the samples collected, are shown in Figures 3.9 and 3.10. Detailed descriptions and photographs of the rocks collected are included in Appendices A08-A10, and images of outcrops are in Appendix A07.

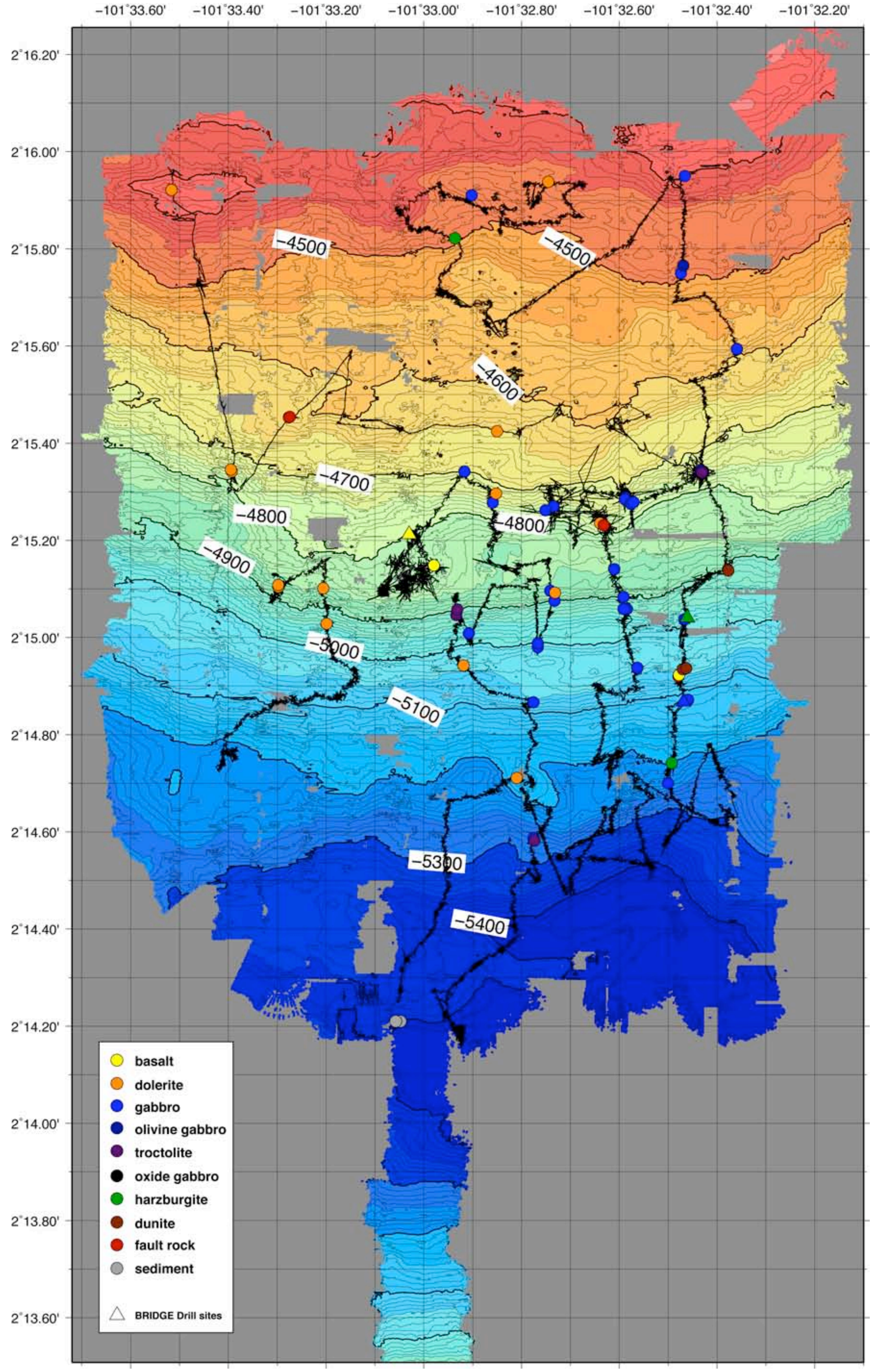

Figure 3.9. Location of near-bottom dive tracks on Isis swath bathymetry map from area A, together with a preliminary interpretation of lithological types (N.B. some of these may change when we have viewed the samples in thin section post-cruise.

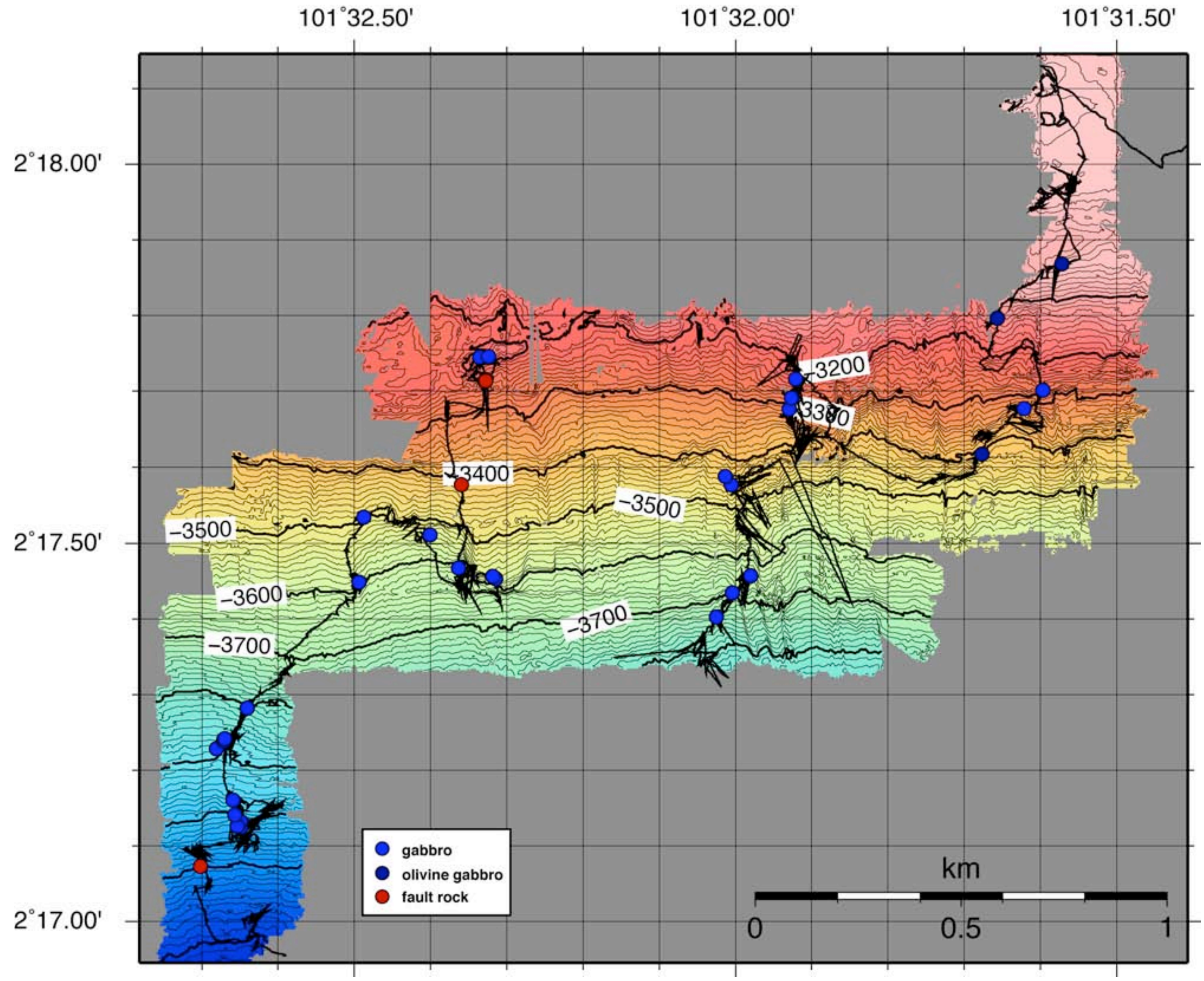

Figure 3.10. Location of near-bottom dive tracks on Isis swath bathymetry map from area C, together with a preliminary interpretation of lithological types (N.B. some of these may change when we have viewed the samples in thin section post-cruise.

Samples were collected using the manipulator arms of *Isis*. Great care was taken to ensure that they were taken from *in situ* outcrop rather than the far easier task of picking up loose material, however 'local' it appeared. Because of the significant amount of talus present and even greater coverage of pelagic sediment, outcrops of *in situ* bedrock were often few and far between. Such outcrops as there were were often visible only on their steep sides, their upper parts being blanketed in pelagic sediment. This is one reason why we found the BRIDGE drilling operations to be so difficult: with a downward-looking video, it was hard to spot outcrops even when directly over them. Only in a few places, more typically on the intra-rift ridge, were outcrops more extensive than a few tens of square metres, and in these places they were often extremely steep.

Rock types recovered by *Isis* range from harzburgite, dunite, troctolite, olivine gabbro and other gabbro lithologies, to dolerites and basalts. In all 145 samples totalling 760kg were collected, with the largest single dive haul being 157kg (dive 73, with 27 samples). The manipulator arms were strong enough to pick up samples as large as 45cm long and weighing up to 27kg; these would typically have to be laid on top of the baskets.

Our detailed mapping (Figs. 3.9 and 3.10) indicates a more complex distribution of rock types across Hess Deep than suggested by previous investigations, and requires significant refinement of presently accepted models for the structure and tectonic evolution of the rift. Importantly however, the ocean crustal stratigraphy at Hess Deep can still be re-constructed enabling primary science questions regarding fast-spread lower crustal accretion mechanisms to be addressed in post-cruise study of the samples collected. The proposed IODP drilling (Proposal 551-Full5, Gillis et al.) will be enhanced and strengthened by our new findings with more confidently established geological context of potential drill sites.

Interpretation of the distribution of rock types and of the morphology and structure of Hess Deep, whether on a local or regional scale, is beyond the scope of this report and will be done post-cruise.

Chapter 4. The BRIDGE Seabed Rock Drill

The British Geological Survey (BGS) 'BRIDGE' seabed drill is designed to take metre-long orientated rock cores from hard substrates in full ocean depths (now up to 5500m). It is so named because the original development of the drill was funded by the NERC BRIDGE ('British Ridge Inter-Disciplinary Global Experiment') programme in 1996-98 [Allerton et al., 1999]. All subsequent development has been funded by the BGS directly.

The device utilises a high-speed rotary diamond drill mounted vertically on a tripod frame. It has the unique ability (for a seabed device) of being able to take geographically orientated cores. A scriber is fitted immediately above the core catcher on the inside of a non-rotating inner core barrel, and carves a scratch into the core as it enters the barrel. The scriber is fixed relative to the drill frame, and its orientation measured by means of two compasses mounted on the frame. Combined with readings from the accompanying pitch and roll sensors, the geographical orientation of the cores can be recovered. A video camera on the drill frame allows the operators to assess the seabed and find suitable outcrops to drill. Core diameter is 35mm.

The BRIDGE drill was deployed on a 17.5mm armoured coaxial power fibre-optic and hoist cable, allowing real-time video to be transmitted to the surface. It was first used in this way on cruise JC007, in spring 2007; prior to that a conducting cable had been used. For navigation a USBL beacon was mounted on the rig, in responder mode, allowing the drill's position to be monitored during operations.

Although collecting orientated cores had been a key part of the science plan for JC21, ultimately we were only able to devote one day to drilling operations during the cruise, making only three deployments of the BRIDGE rock drill. None of these sites (BR201, BR202 and BR203) recovered *in situ* orientable material. Unfortunately drilling was the principal casualty of the eight days lost when operations were curtailed for the emergency transit to Panama.

On the deployments we did make we found it difficult to navigate the drill onto specific targets because the positioning errors (±25m) with the USBL navigation at these water depths (5000m) were greater than the size of the only suitable targets we identified from the *Isis* near-bottom video surveys (tens of square metres only). Because of our straitened circumstances we did not have time to investigate potential solutions to these issues as we would otherwise have done; priority was instead given to the more straightforward and highly successful sampling with the ROV.

Full details of the drilling operations is given in Appendix A06. Descriptions and photos of the hard-rock cores we did collect from the three sites are given in Appendices A07-A10.

Chapter 5. Sample Descriptions

5.1 Introduction

All samples were described on board based on macroscopic observations made on cut surfaces. The following information was recorded for each sample in spreadsheets:

- *rock name*
- *primary mineralogy*
- *mode (visual estimate)*
- *minimum, maximum and average grain size of each of the primary phases*
- *habit of each of the primary phases*
- *magmatic deformation intensity*
- *crystal-plastic deformation intensity*
- *cataclastic deformation intensity*
- *vein density*
- *fracture density*
- *total alteration*
- *alteration phases*

In addition, a summary sheet was prepared for each sample containing sample location, outcrop description, sample picture and a brief summary of lithology, structure and alteration.

5.2 Igneous petrology

Igneous petrology descriptions were done by Johan Lissenberg, Kerry Howard, Heidi Hansen and Masako Tominaga. Each sample was assigned a rock name using the following criteria, which closely follow those used during (I)ODP hard rock legs and described in Blackman et al. (2006).

Plutonic rocks are classified by pre-alteration mineralogy and mode largely following IUGS guidelines (Fig. 5.1; Streckeisen, 1974):

Harzburgite:	>95% olivine+orthopyroxene, olivine>orthopyroxene, olivine <90%
Dunite:	>90% olivine
Troctolite:	olivine+plagioclase >95%, olivine >10%, plagioclase >10%
Olivine gabbro:	olivine+plagioclase+clinopyroxene, none of which <5%
Gabbro:	plagioclase+clinopyroxene >95%, plagioclase >10%, clinopyroxene >10%
Gabbronorite:	plagioclase + clinopyroxene + orthopyroxene, none of which <5%

Following Leg 304/305 procedures (Blackman et al., 2006), we used several **modifiers** for rock names:

'Olivine-bearing' is used when olivine in gabbroic rocks forms between 1 and 5 % of the mode.

'Orthopyroxene-bearing' is used for gabbroic rocks with orthopyroxene contents between 1% and 5%.

'Oxide' is used as a modifier for gabbroic rocks if oxides form >2% of the mode.

'Disseminated oxide' is used for gabbroic rocks if oxides form between 1% and 2% of the mode.

'Plagioclase' is used as a modifier for dunites where plagioclase forms <10%.

In addition to the classification of plutonic rocks, we used 'basalt', 'dolerite' and 'cataclasite'. Basalt was used to describe aphanitic rocks, which may contain vesicles and/or phenocrysts, and may have glassy rims. We thus used basalt as a textural term; formal classification using the IUGS compositional scheme for volcanic rocks awaits the acquisition of geochemical data. Dolerite was used to describe fine-grained rocks with sub-ophitic to ophitic textures and acicular plagioclase. Basalt and dolerite were assigned modifiers based on phenocryst content; 'aphyric' for rocks with <1% phenocrysts and 'sparsely phyric' for rocks with 1%-5% phenocrysts.

Cataclasite was used for rocks that suffered significant cataclastic deformation (see below); generally, no progenitor could be distinguished for these rocks. If the igneous rock type could be deduced, the term was instead used as a modifier: e.g. 'cataclastic dolerite'.

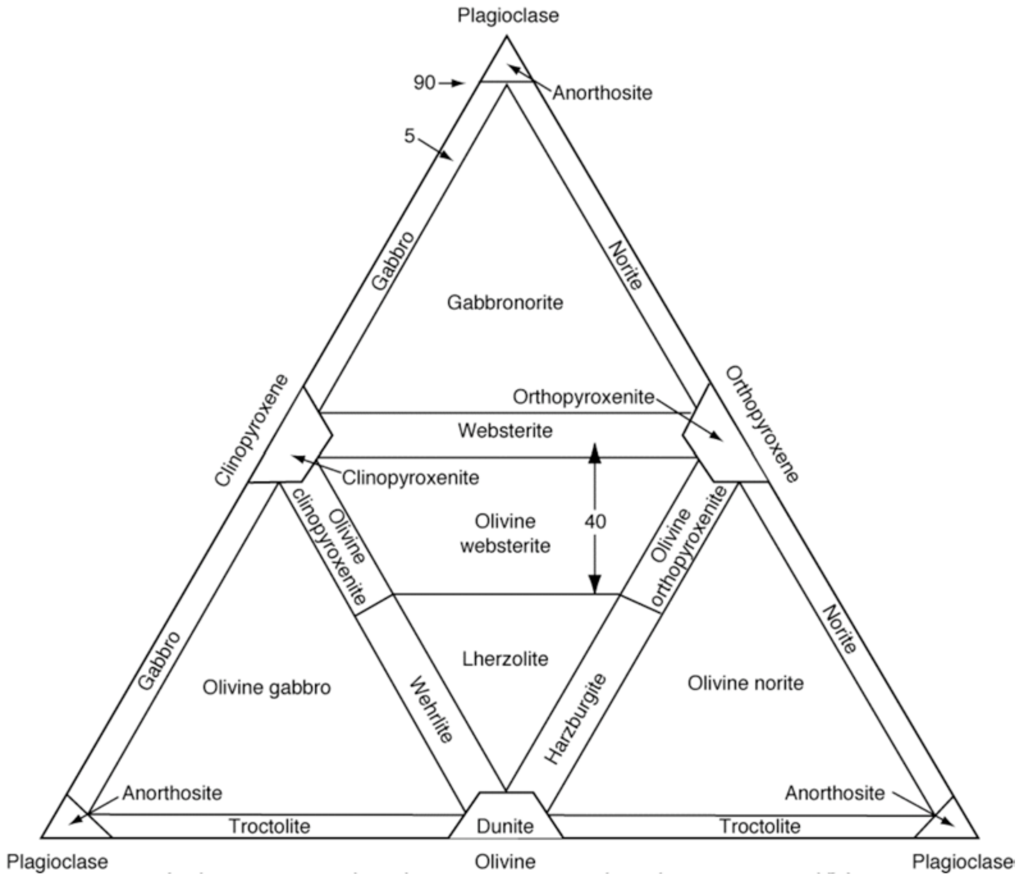

Figure 5.1: Classification scheme for plutonic igneous rocks after Streckeisen [1

Rocks were assigned a **grain size** based using the following scale:

Fine-grained:	average grain size <1 mm
Medium-grained:	average grain size 1-5 mm
Coarse-grained:	average grain size 5-30 mm
Pegmatitic:	average grain size >30 mm

For samples with a range of grain sizes (e.g., varitextured gabbros), multiple grain size terms may be used.

All samples were assigned a **textural term**, using the following conventions:

Gabbros:

1)	*Equigranular*	similar grain size throughout sample
2)	*Varitextured*	variable grain size and/or texture throughout sample
3)	*Poikilitic*	sample contains oikocrysts enclosing chadacrysts

Peridotites:

1)	*Coarse granular*	grain size >10 mm
2)	*Medium granular*	grain size between 3 and 10 mm
3)	*Porphyroclastic*	presence of porphyroclasts in deformed matrix
4)	*Mylonitic*	strong grain size reduction due to deformation

Basalts and dolerites:

1)	*Aphanitic*	individual grains cannot be distinguished
2)	*Fine-grained*	grain size > 1 mm but can be distinguished
3)	*Medium-grained*	grain size 1– 5 mm
4)	*Porphyritic*	contains phenocrysts
5)	*Seriate*	continuous range of crystal sizes
6)	*Ophitic*	clinopyroxene encloses plagioclase
7)	*Sub-ophitic*	clinopyroxene partly encloses plagioclase

Mineral shapes of all primary phases were described using the following conventions for porphyroclasts (1-4) and primary igneous grains (5-9):

1) *Equant*	-	aspect ratio <1:2
2) *Subequant*	-	aspect ratio 1:2 to 1:3
3) *Tabular*	-	aspect ratio 1:3 to 1:5
4) *Elongate*	-	aspect ratio >1:5
5) *Euhedral*	-	well-developed habit
6) *Subhedral*	-	moderately developed habit
7) *Anhedral*	-	poorly developed habit
8) *Interstitial*	-	crystal fills spaces between framework of other crystals
9) *Oikocryst*	-	relatively large crystal enclosing multiple smaller crystals of another phase

5.3 Structural petrology

Structural descriptions were done by Benoît Ildefonse, using the same conventions as those defined in the Methods chapter of the IODP Expedition 304-305 Proceedings (Blackman et al., 2006), and derived from several earlier hard rock ODP Legs. These procedures may be used with both crustal and mantle rocks. Each structural feature (magmatic and solid state foliations; cataclastic deformation intensity; vein density; fracture density) was characterized by a value on a semi-quantitative, empirical intensity scale (Fig. 5.2). This characterization was complemented by a brief description whenever appropriate. Orientations of planar features in orientated Bridge Drill cores were measured in the core reference frame, with the scribed mark indicating a provisional North.

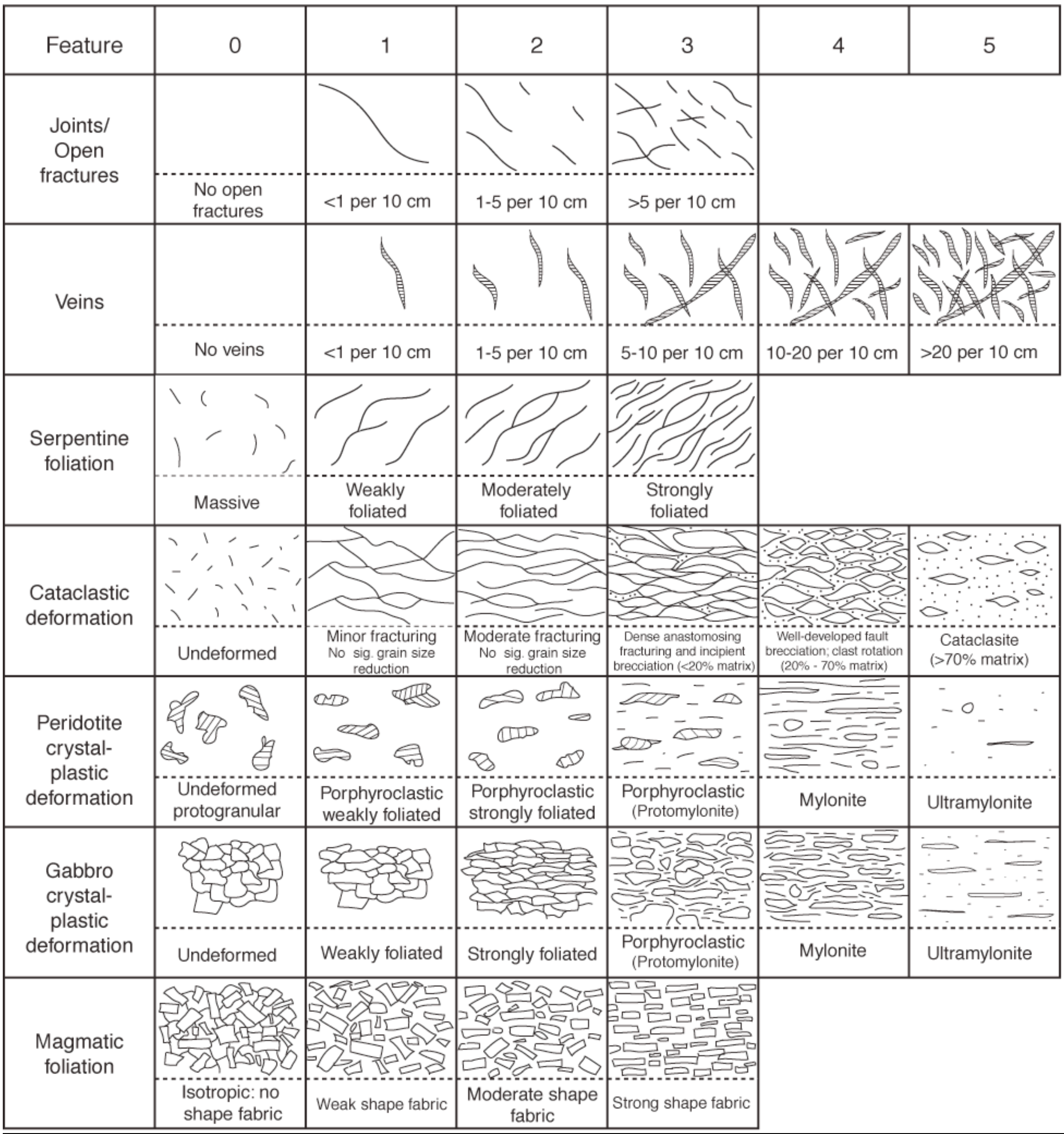

Figure 5.2: Scales used to describe deformation intensity

5.4 Metamorphic petrology

Descriptions of the metamorphic and alteration assemblages were done by Michelle Harris, Damon Teagle and Kathy Gillis.

First, the overall alteration intensity of the sample was described and quantified on a scale of fresh (<1%), slight (<10%), moderate (10-50%), high (50-90%) and complete (>90%). Alteration was then described for each of the primary igneous phases (where applicable), recording the secondary phases and estimates of the percentage of the mineral replaced where possible. General alteration features of the sample were recorded as comments.

Veins were logged separately with vein thickness, composition, morphology, cross cutting relationships, halo and halo composition all recorded.

Chapter 6. Daily Narrative

The purpose of this section is to give a brief summary of operations on a daily basis, written at the time. It includes any other happenings of interest, and gives a brief perspective on how our ideas developed as the cruise progressed, both with respect to operational strategy and our scientific thinking. A visual summary of all operations is given in Figure 6.1. Of the 24 allocated days of science time, approximately 14.5 days were devoted to *Isis* operations, 1 day to drill operations, and 8.5 days were lost to various equipment problems and (most of all) to the need to suspend operations in the survey area in order to make a compassionate evacuation of a crew member to Costa Rica.

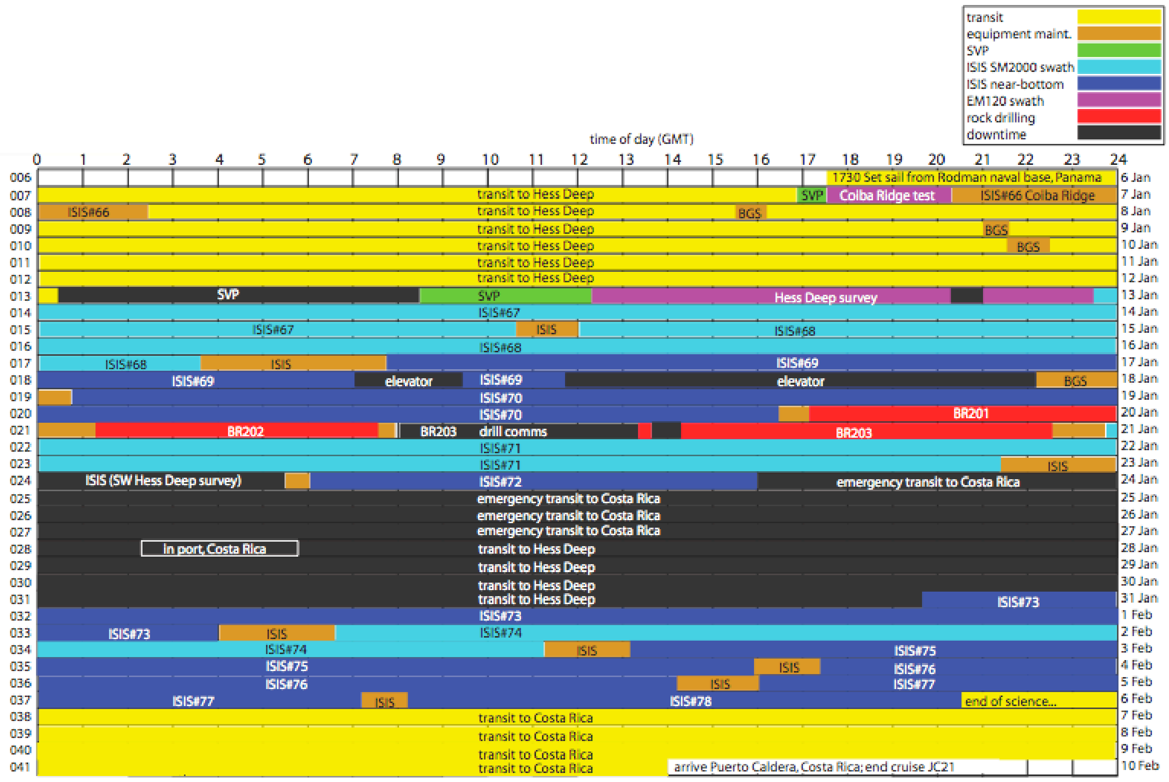

Figure 6.1. Gantt chart summarising operations during cruise JC21.

Sunday 6th January 2008 (2008/006Z)

In port, at a bunkering berth at the Rodman Panamanian naval station, 8°57.10'N 79°34.38'W, then set sail for survey area (start cruise JC21). Weather hot and sunny; seas calm.

The last members of the shipboard party, including the PSO, arrived in Panama in the early hours of the morning of 6th January and were brought straight onboard RRS *James Cook*. The PSO was immediately informed of the situation regarding the communications from the vessel, *viz.* that the V-sat communications system that normally provided a live internet/e-mail/phone link had failed and that replacement parts for the system could not be sourced within a reasonable period. Although this had been known by Southampton for more than a week, neither the PSO nor the Master had been informed ahead of time.

Ship to shore communications for the duration of the cruise will be restricted to the sat-B satellite phone and fax from the bridge only, though attempts will be made to establish a limited e-mail link in due course.

The PSO was informed by the Master that the ship had been asked to vacate the bunkering berth it was currently occupying by noon local time (GMT-5). No indication had been given as to when or where another berth would be found. Given that all personnel were now on board ship, and all provisioning completed, it was decided to depart for sea as soon as possible, The science party were informed, and had a brief opportunity to make phone calls from public payphones near the dock before the gangway was raised in preparation for the ship's departure.

RRS *James Cook* accordingly cast off her moorings at 1230 local time (006/1730Z), and cruise JC21 commenced. She passed beneath the Bridge of the Americas and set sail for the survey area, 18 hours ahead of the original departure time. At a cruising speed of 11kt transit to Hess Deep is estimated at approximately 5 days. A safety briefing was held in the afternoon and the science party signed the ship's muster.

Monday 7th January 2008 (2008/007Z)

Transit to Hess Deep, interrupted by a test deployment of Isis (dive #66). Local noon fix (GMT-5): 5°33.4'N 81°52.1'W; average speed 12.0kt; distance travelled 268nm; weather hot and sunny, seas calm..

The *Isis* group requested that they be allowed to carry out a wet test of the ROV. Noting (from global satellite bathymetry maps) that coincidentally we were close to a shallow region – Coiba Ridge – we asked if the scope of this test could be widened and a short bathymetry survey conducted. This had several aims: to calibrate the ROV swath bathymetry system; to make an assessment of an optimum towing altitude; to give the science party some idea of what would be required of them when the survey proper started; and, not least, to give Donna, Pierre, Steve and Masako a test data set to gain experience of data processing prior to arrival on site.

The sound–velocity probe was deployed at 5°33.43'N 81°52.15'W (744m water depth) and run to 700m. With the ship's EM120 swath bathymetry now calibrated, a brief (~1 hour) swath survey of a conveniently nearby seamount (295m water depth) was conducted until the *Isis* team were ready to deploy the ROV. *Isis* was initially launched at 007/2018Z but a problem was immediately found with a console in the control shack. The vehicle was retracted into its A-frame until the panel was exchanged. It was relaunched at 007/2057Z and wet tests conducted. This being satisfactory, the ROV was taken down to mid-water depths and a series of turns ('Tivey turns') conducted in order to calibrate the magnetometer. A short survey was then carried out to calibrate the SM2000 swath bathymetry. *Isis* was towed at 100m altitude from 5°30.0'N 81°51.8'W to 5°30.0'N 81°51.6'W (approximately 350m W to E) and then back over a reciprocal course. By comparing the two profiles any misalignment of the swath sensor can be identified and corrected for. *Isis* was towed at approximately 0.4kt, so each pass took approximately 30 minutes, and 10 minutes to turn the vehicle around. Part of the same swath was also run again at 150m altitude, but it was found that the bottom detection was poor at this height and the swath width obtained was actually narrower than that acquired at 100m towing altitude. The doppler system actually detected seafloor at up to 192m altitude, but the signal was inconsistent. At the end of the survey the ROV was taken down to the seabed briefly to give the science party experience of the kind of images visible on the different camera systems carried on board *Isis* (rippled sediments and white, probably biological, mats). The ROV was brought on deck again at 008/0223Z, and the transit to Hess Deep resumed. The total time of the Coiba Ridge test survey was approximately 6 hours.

Ship's clocks were retarded one hour on Monday night, to GMT-6.

Tuesday 8th January 2008 (2008/008Z)

Transit to Hess Deep. Local noon fix (GMT-6): 5°05.0'N 84°23.3'W; average speed 10.2kt; distance travelled 158nm (total distance 426nm); weather heavy rain, light-moderate seas.

In the morning a one hour test deployment of the BRIDGE rock drill was made by the BGS team. Problems were found with the flush pump and with the echosounder, but these were not thought to be serious.

Kathy gave a talk to the science party explaining the regional setting of Hess Deep and reviewing previous expeditions to the area. Donna then gave a brief review of yesterday's *Isis* test dive. She and the 'GMTers' (Pierre, Steve, Masako) are working on the SM2000 swath data we collected and are making good progress towards producing a preliminary bathymetry map.

In attempting to print out a base map of the existing bathymetry of the survey area, we found out that the A0 plotter on board is only able to print in monochrome: the colour print heads are broken and no spares are on board. The PSO was told by the NMF personnel on board that the problem had been known about since cruise JC19 and had been reported to Southampton, but that nothing had been done. Our ability to print in colour is now restricted to an A3 inkjet and A4 colour laser printers.

Wednesday 9th January 2008 (2008/009Z)

Transit to Hess Deep. Local noon fix (GMT-6): 4°23.7'N 88°31.7'W; average speed 10.4kt; distance travelled 250nm (total distance 676nm); weather overcast, light seas.

A second test deployment of the BRIDGE rock drill was made at approximately 009/2200Z to test the flush pump and box the drill compasses. Although the flush pump test went according to plan, the drill rig could not be rotated in the water column rapidly enough to allow the calibration to be made. An acoustic transponder beacon was fitted to the drill frame before the deployment and was successfully tracked in water depths of ~100-200m beneath the ship.

At the daily science meeting Chris gave an overview talk on fast spreading ridge magma chambers and constraints from the Oman ophiolite. Science party members all discussed their research interests and aspirations for post-cruise research and collaborations with other science party members. Earlier, Chris, Damon and Kathy had met with the Master and other key members of the ship's crew and scientific support group for what will become regular daily meetings to review proceedings.

Clocks were retarded one hour further on Wednesday night, to GMT-7. The ship will remain on this time zone for the duration of the cruise until passing back through the equivalent longitude on the transit back to Panama.

Thursday 10th January 2008 (2008/010Z)

Transit to Hess Deep. Local noon fix (GMT-7): 3°49.8′N 91°56.1′W; average speed 8.8kt; distance travelled 207nm (total distance 883nm); weather overcast, light seas.

Unfavourable currents have been reducing our cruising speed on two engines (of the four on board) to as little as 9kt, so a third engine was started up in order to bring the estimated time of arrival back to late on Saturday night (12th January). Another test of the BRIDGE rock drill was conducted. This time the drill was successfully rotated in the water column, by the expedient of fixing a plank of wood to the core barrel to act as a paddle and spinning it. A final calibration of the compasses on the drill will be made prior to the first deployment on site.

At the daily science meeting Benoît spoke about the Mission Moho initiative and broad-scale mid-ocean ridge drilling strategies, and Damon reviewed results from ODP Hole 1256D. In the evening Chris gave a talk to the ship's crew and scientific support personnel about the aims and objectives of the cruise, and outlined our intended survey strategy.

Plans were drawn up for the first 48 hours or so of operations at the survey area. First of all we will run a sound-velocity profile right in the axis of Hess Deep and then carry out an EM120 (ship-mounted) swath bathymetry survey over the rift valley: two E-W swaths each of ~16nm length, run at 4kt in the quest for optimum data quality. We will then switch to *Isis* ROV operations, starting with a grid survey in which we will tow the vehicle from south to north from the axis of Hess Deep northwards up the slope from ~5400m to ~4400m and back again. Results to date from the Coiba Ridge test dive suggest a 150m spacing between lines and 100m towing altitude to be a safe estimate to ensure complete coverage.

Friday 11th January 2008 (2008/011Z)

Transit to Hess Deep. Local noon fix (GMT-7): 3°07.2′N 96°12.8′W; average speed 11.3kt; distance travelled 259nm (total distance 1142nm); weather light cloud, light seas.

A fire drill was held in the morning and a safety video shown to the science party. The towed magnetometer was tested, the ship slowing to 7kt for deployment and recovery. The system appeared to work as it is meant to.

Tony and Johan gave presentations at the daily science meeting: Tony on Expeditions 304/305 palaeomagnetism and Johan on gabbros from the Annieopsquotch ophiolite and Mid-Atlantic Ridge. For the 'rock group' members of the science party the day was otherwise spent mainly in discussing procedures for the coming operations. For core description, spreadsheets were devised based upon those used on recent ODP/IODP cruises (e.g. Exps. 304/305), and visual core description templates based upon previous seabed drilling cruises (JR63, JC007) were discussed. The GMTers continued to wrestle with artefacts in the SM2000 swath test data set. Michelle, Kerry and Heidi devised a system to allow unique identification of compartments in four wire baskets fabricated by Dave Turner for the *Isis* sample sled. Two are carried on the vehicle and the second pair are to be put in boxes on the seabed elevator, to be exchanged when the first two are full.

A gathering was held in the PSO's cabin in the evening to mark the last night before the science party starts working shifts.

Saturday 12th January 2008 (2008/012Z)

Transit to Hess Deep, and arrival on site. Sound velocity calibration. Local noon fix (GMT-7): 2°22.6'N 100°41.4'W; average speed 11.3kt; distance travelled 272nm (total distance 1414nm); weather light cloud or sunny, wind 14kt from 200°, moderate seas.

The science party commenced shift work from (local) noon onwards. The daily science meeting was held in the main lab, as it will now be for the remainder of the operational period. Procedures for each of the operational scenarios envisaged were run through in detail. Chris explained how the BRIDGE drill operations were conducted and how he thought best to deal with core and ROV sample curation.

At 013/0015Z (1715 local time on Saturday 12th January) we arrived on site over the axis of Hess Deep (2°14.13'N 101°32.54'W, depth 5430m). To celebrate the arrival on site, the science party assembled on the monkey island on top of the bridge and toasted the Welsh flag as it was raised up the ship's mast, accompanied by the strains of 'Land of our Fathers' played on the mandolin by the PSO.

Cruise JC21 scientific operations commenced with the deployment of the sound velocity probe. The initial deployment was aborted with the probe at ~2000m when a problem became apparent with the lubrication of a sheave on the starboard gantry. The SVP was brought back onboard and the gantry brought in to fix the auto-greasing system. The probe was launched again 2 hours 40 minutes later and this time deployed to its maximum rated depth of 5000m. Upon recovery it was found that one of the two sensors had not logged any data and the other had only recorded data down to 2000m. A third SVP deployment was made to 5000m and this time the profile was recorded successfully. A total of 7 hours 35 minutes was lost during the two unsuccessful deployments.

Sunday 13th January 2008 (2008/013Z)

On site, Hess Deep. Completion of sound velocity calibration followed by EM120 swath bathymetry survey followed by Isis deployment (dive 67). Local noon fix (GMT-7): 2°17.7'N 101°25.0'W; average speed 10.6kt; distance travelled 52nm (total distance 1466nm); weather cloudy to fine and clear, wind 10kt from 185°, light sea and low swell.

The EM120 (surface) swath bathymetry survey of Hess Deep began belatedly early on Sunday morning (013/1313Z): two swaths E-W within the Deep to give coverage of the main area. The survey was run at 4kt and the data quality looks very good. The towed magnetometer was also deployed. At 013/2012Z the ship lost propulsion during a turn and the ship drifted until power was restored. A control problem on the DP desk on the bridge was suspected, and it went away when the system was rebooted. The ship was then manoeuvred back to the position it was in when power was lost and the survey resumed. The magnetometer had been brought in when the propulsion had been lost but was redeployed shortly afterwards. Some 48 minutes was lost due to this episode.

The swath survey finished at the start point of the first operational *Isis* dive (#67). The vehicle was launched at 013/2335Z at 2°13.48'N 101°32.01'W, in 5010m water depth, and dived without incident down to the start point of the survey. Initially the magnetometer on *Isis* did not appear to be working, but contact was restored as the vehicle got deeper. The Tivey turn was carried out near the bottom. Once this had been done the SM2000 swath survey commenced, moving northward at approximately 100m altitude at ~0.3-0.4kt.

Monday 14th January 2008 (2008/014Z)

On site, Hess Deep. Isis dive 67 (SM2000 swath survey). Local noon fix (GMT-7): 2°14.2′N 101°32.8′W; weather sunshine and showers, wind 14kt from 190°, slight sea and low swell.

Operations continued with *Isis*, collecting swath bathymetry data using the SM2000 system from a target altitude of 100m. The system is behaving stably and the swath appears to be working well. From the strength of the returns on the surface monitor the SM2000 looks to be able to acquire more and better data when running up and down slope rather than parallel to the contours. However, we did find that the vehicle wasn't able to track the bottom well at speeds of greater than 0.3kt, rather than the 0.4kt we had predicted; hence we will have to revise downwards our estimate of the length of track we can cover over the course of a dive. Donna and Pierre have partially processed the data from the first two N-S lines, though there are still some difficulties in inputting some of the data/navigation streams. So far it appears that the data are quite noisy and a lot of cleaning will be required. Swath widths appear to vary from ~100m at worst to nearly 300m. It was therefore decided to widen the spacing between the next two lines (67-3 & 67-4) from 150m to 175m. The *Isis* group estimate that the vehicle will probably need to be recovered sometime overnight Monday-Tuesday to replenish the oil reservoir.

Tuesday 15th January 2008 (2008/015Z)

On site, Hess Deep. Isis dives 67 and 68 (SM2000 swath survey). Local noon fix (GMT-7): 2°14.1′N 101°32.6′W; weather clear and fine, wind 6kt from 180°, slight sea and moderate long swell.

After completing four full swath lines, oil reservoir levels on *Isis* had fallen to the minimum safe level. At 015/0734Z the decision was therefore taken to terminate dive 67 and recover the vehicle. *Isis* was brought on deck at 015/1045Z. The dive has yielded high-resolution bathymetry over an area approximately 900m wide between 2°14.6′N and 2°16.0′N (with the first line extending south to 2°13.5′N, across the axis of the Deep) between longitudes 101°33.1′W and 101°32.65′W. Although much more processing will be required in order to remove artifacts, the data reveal in vastly greater detail the nature of the slope north of the nadir of Hess Deep between 5400m and 4400m. It will be invaluable in guiding our subsequent investigations with both ROV and drill.

At the end of dive 67 the ship was moved slightly to the north and east, to 2°16.000′N 101°32.651′W, and *Isis* redeployed at 015/1152Z (dive 68). We offset the ship so we could run the first line of this dive in a down-slope direction (N to S), as this appears to give slightly better quality data. *Isis* reached the bottom and resumed surveying at 015/1424Z. Line 68-1 lies 175m to the E of line 67-4 and overlaps with it to ensure continuous coverage. Succeeding lines will extend the survey to the east. After examining the navigated data from the last lines of dive 67 it was decided that we could safely increase the line spacing to 200m for dive 68.

Wednesday 16th January 2008 (2008/016Z)

On site, Hess Deep. Isis dive 68 (SM2000 swath survey). Local noon fix (GMT-7): 2°15.9'N 101°32.2'W; weather clear and fine, wind 10kt from 183°, slight sea and low long swell.

The *Isis* dive 68 swath survey continued all day, working progressively eastwards. Although the vehicle behaved flawlessly on bottom, we had problems with the computer onto which the data were being logged in the control van: the MS2000 software package crashed several times and, more seriously, the hard drive filled up far more rapidly than expected (possibly as a result of disk fragmentation problems). It was not possible to transfer data off the acquisition computer and onto the RAID drive whilst collecting new data; hence the survey had to be suspended for an hour on two separate occasions to fre up space. It will be necessary to ensure the acquisition computer's hard drive is emptied and defragmented before each swath dive in future (if we do any more).

Four complete lines were run, spaced 200m apart, and a fifth was started. However, oil levels were not sufficient to allow us both to complete this line and run an east-to-west calibration line across the previous ones. The calibration line had two aims: (i) to generate data over the same area in order to allow us to investigate the still-unresolved vehicle attitude correction problems; and (ii) to check for navigational mismatches between lines, particularly because we have still been unable to gain access to the doppler data. We curtailed the fifth line (run from north to south) at latitude 2°15.18'N and turned west, swathing towards the prominent bench we had identified in the dive 67 data. In the end there was enough time remaining for the calibration cross-line to be extended right across the line 67 survey area as well as line 68.

Dinner included (for a privileged few) fresh squid caught last night by Viv Wythe, the Deck Engineer. He and Heidi caught even more on Wednesday night, enough for tomorrow night's entrée.

Thursday 17th January 2008 (2008/017Z)

On site, Hess Deep. Isis dive 68 (end) and near-bottom dive 69 (ongoing). Local noon fix (GMT-7): 2°14.95'N 101°32.9'W; weather clear and fine but with occasional light showers, wind 10kt from 187°, slight sea and low long swell.

Recovery of *Isis* from the seabed at the end of dive 68 started at 017/0039Z, and the vehicle was brought onboard at 017/0345Z. Checking of the ROV following the routine oil fill revealed a hydraulic leak with one of the thrusters, necessitating its replacement. The magnetometer was reattached. The SM2000 swath array was removed, along with the side swing arm, to maximise the payload in preparation for the next dive in 'near-bottom mode'. *Isis* was then relaunched at 017/0748Z. The start point of dive 69, 2°14.18'N 101°33.03'W (~5430m water depth) is in the nadir of Hess Deep, at the foot of the first south-facing scarp. The aim of the dive is to work progressively northward up the slope from 5400m to ~4400m over the area swath-mapped in dive 67, characterising the nature of the seafloor, and finding and sampling outcrop wherever possible.

Isis reached the seabed at 017/1134Z and the dive 69 near-bottom survey commenced. The three watches each got to grips with the necessary logging procedures in the ROV control van without any major problems. We traversed half way up the slope to ~5000m water depth in only 8 hours or so, finding very few outcrops and collecting only 4-5 samples. This we realised was probably too rapid a transect, and so we changed tactics, instead running repeated mini-traverses up the steeper scarps to search for outcrops. This was more successful and we will probably need to apply this to the lower slopes in a subsequent dive or dives.

Because of our increased sampling rate in the later part of the day we decided to deploy the elevator overnight Thursday-Friday and offload the two baskets carried on the *Isis* sled. We aimed the elevator in the centre of the largest flat feature we have identified: the 200m-wide bench between 2°15.1′ and 2°15.2′N and monitored its descent using USBL navigation. It took two hours to reach the seabed at 4825m depth. Significantly it drifted 355m (in direction 253°) from its launch position – fortunately still (just) on the bench – revealing hitherto unsuspected E to W currents throughout the water column.

Friday 18th January 2008 (2008/018Z)

On site, Hess Deep. Isis near-bottom dive 69 plus elevator recovery; then BRIDGE drill calibration and launch of Isis for near-bottom dive 70. Local noon fix (GMT-7): 2°14.9′N 101°33.4′W; weather clear and fine, wind 11kt from 187°, slight sea and low long swell.

Soon after the elevator landed we drove *Isis* to it in order to change the full sample baskets from the sled for the empty ones sent down in the big wooden boxes mounted on the elevator platform. It took approximately two hours to change the baskets over, partly because the elevator was on a slight slope (~15°) and the box lids wouldn't stay open. The tilt of the elevator is probably the reason why we had great difficulty communicating with it as soon as it was on the seabed. This had serious implications not only for triggering its acoustic release mechanism but also for tracking it during its ascent and recovering it at the surface. Although surveying resumed briefly, after a couple of hours it was decided that we had to stop and return to the elevator to try to resolve the problem. Getting it to the surface in daylight hours was a factor that guided this decision. Five hours later the elevator release was triggered manually using one of the *Isis* manipulator arms. Of course the USBL tracking was restored as soon as the rig returned to the vertical position as it rose through the water column. Because of *Isis*'s oil levels we decided there was little point in continuing the dive after the elevator recovery and so we brought it up to mid-water levels during the elevator recovery.

The elevator recovery was not straightforward. Because *Isis* was still in the water the ship could not be moved at more than 0.5kt; however, the surface currents were in excess of 2kt. The ship was positioned down-current of the point the elevator broke surface, ready to hook it from the starboard side of the ship as it floated by. Unfortunately its recovery float line got caught in the bow thruster and the elevator was dragged beneath the ship, emerging on the port side and rapidly floating away behind the vessel. Thankfully it was not smashed and did not foul the *Isis* cable on the port side afterdeck. The mob boat was launched immediately, eventually snaring the elevator and towing it slowly (against the current) back to the ship. After a couple of attempts it was finally brought aboard about an hour after it reached the surface. Despite the rough treatment the elevator received the (59kg of) samples in the baskets in the sampling boxes were recovered safely. *Isis* itself was recovered an hour and a half later, ending dive 69.

The samples included harzburgites, dunites, impregnated dunites, troctolites, gabbros (*s.l.*), dolerites, basalts and cataclastic fault rocks: a veritable panoply, but alas not in any conventional stratigraphic order. It became immediately clear that Francheteau et al.'s inference that a layer-cake lower crustal section is exposed here is dangerously misleading, and we will need to work very hard if we are to be able to reconstruct any kind of primary igneous stratigraphy here.

The elevator shenanigans consumed approximately 13 hours of shiptime altogether. It is clear from our experience that simply bringing *Isis* up to the surface, emptying its baskets, refilling it with oil and relaunching it is far more time-efficient: a ~5-6 hour round-trip on-bottom to on-bottom. We will not use the elevator again.

Once *Isis* was on deck and being serviced a final calibration of the BRIDGE drill was performed. *Isis* was then relaunched (dive 70), again in near-bottom mode, with the intention of ground-truthing and sampling the region swath-mapped during dive 68.

Saturday 19th January 2008 (2008/019Z)

On site, Hess Deep. Isis near-bottom dive 70. Local noon fix (GMT-7): 2°14.8′N 101°32.4′W; weather cloudy to clear and fine, wind 8kt from 200°, slight sea and low long swell.

Isis dive 70 continued throughout the day, thankfully with less incident than yesterday. Once again we found it very difficult to locate outcrops, either for sampling with the ROV there and then or as potential BRIDGE drill sites later; this despite searching much more carefully on the lower slopes between 5400m and 5000m. Eventually we meandered northwards up the slope to the shallowest region swathed during dives 67 and 68 (~4700m to 4500m depth; 2°15.40′N to 2°16.0′N), sampling wherever possible.

Sunday 20th January 2008 (2008/020Z)

On site, Hess Deep. Isis dive 70 (end) then BRIDGE drill site BR201 and BR202 (ongoing). Local noon fix (GMT-7): 2°15.21′N 101°33.01′W; weather cloudy to clear and fine, wind 9kt from 195°, slight sea and low swell.

Isis was brought to deck in the morning as oil levels ran low and the baskets were filled to (slight over-) capacity with some 65kg of rock samples. Our plan was then to switch to BRIDGE drill sampling of targets we had identified during the ROV dives. The only possible contenders we had picked out were all very small (typically a few square metres only), in deeper water than the drill had ever been before, steep and partially sediment blanketed, so we were aware that the process would be difficult. Nevertheless, we hoped that by tracking the drill using USBL navigation (as was done very successfully on cruise JC007) and moving the drill by moving the ship until within range of the drill's real-time video camera we could identify the sites visually.

Site BR201 was the shallowest and flattest of the localities we had identified, lying on the mid-slope bench at 2°15.204′N 101°33.010′W and 4810m water depth. Immediately following deployment we had difficulties in locating the drill using the USBL transponder, and this continued for the remainder of the dive. Many of the intermittent fixes we did have showed the drill to be up to 100m WSW of the ship, perhaps as a result of the same current that caused the elevator to drift so far; others, however, seemed to be directly beneath the ship. The uncertainty made it impossible to navigate the drill to the intended target, which was only a few square metres in diameter. This problem was compounded by our inability to see the bottom effectively from the onboard video camera: as we approached the bottom we found that the considerable amount of pelagic sediment that blankets the area was being entrained into the water column by the suction effect of the drill bobbing up and down with the ship's heave. Finally we drilled on a sedimented slope with scattered talus, in the hope that the sediment might be thin enough that we could find basement beneath. This proved to be a forlorn hope and we duly recovered 30cm of incohesive brown pelagic sediment. However, we also found a chunk of pillow lava wedged in one of the feet of the drill, presumably from one of the scattered talus blocks at the site.

In the afternoon, as the drill was about to be brought on board following the operations at Site BR201, a water pipe burst in the winch room. The recovery was halted as the leak was traced and stopped off and then the spillage cleaned up. As a result, the water supply to several of the scientists' cabins has been disrupted. Kerry, Michelle, Heidi and Masako were forced to move to other vacant cabins for a while; Kerry for the remainder of the cruise.

The drill was redeployed at Site BR202, at 2°15.036′N 101°32.466′W (4971m).

Monday 21st January 2008 (2008/021Z)

On site, Hess Deep. BRIDGE drill sites BR202 and BR203, then Isis swath dive 71 (ongoing). Local noon fix (GMT-7): 2°14.89′N 101°32.45′W; weather overcast, wind 12kt from 167°, slight sea and low swell.

Drilling operations at Site BR202 proved to be just as frustrating as at BR201. The target was a rocky outcrop at the top of a steep spine in between talus chutes. We hoped the lack of pelagic sediment here might make it easier to see the target once we got close to it. The USBL did give more frequent fixes on this dive – again, consistently ~100m WSW of the ship – but in the end the outcrop was just too small for us to find even though we think we were very close to it. We drilled a rubbly surface in the hope that it was outcrop but recovered only a small (orientated) plug of what was almost certainly talus, of tectonised harzburgite.

For our third attempt at drilling, Site BR203, we aimed for what we believed to be one of our biggest targets so far: a big block several metres high and (we thought) some tens of square metres in extent, though in very deep water (~5100m). We offset the ship 100m ENE of the intended target to account for the apparent drift due to currents in the water column. Initially the USBL tracked the drill very well, which indeed offset to the WSW as predicted, such that we were only ~25m away from the target as the drill approached the bottom. Unfortunately, at about 100m above bottom communications to the drill ceased abruptly, and we were compelled to recover the drill to deck. The faulty connector was traced and replaced and the drill redeployed, then another failure occurred and the drill recovered yet again. After this third deployment we had no further problems with the drill itself; however, the USBL fixes were now very intermittent. Furthermore, the positions they gave consistently put the rig directly beneath the ship, though with spurious depth estimates. When reaching the bottom, therefore, the drill was apparently offset ~100m ENE of the target. Finding nothing on the bottom beneath the rig (though with the same difficulties as before in our vision being obscured by sediment in the water column) we therefore towed the drill slowly WSW, checking the bottom as we proceeded. As we positioned ourselves over the target, the (still intermittent) USBL fixes abruptly switched to indicate that the drill was over a region 100m WSW of the ship once again… We suspected that the fixes where the drill was offset from the ship were more likely to be correct, as the calculated depths were accurate, but when we dragged the drill back again over the supposed outcrop we never found the target. An attempt at drilling yielded a pebble of olivine gabbro.

Because of our lack of success with the three sites attempted and our severe concerns over our ability to navigate the drill onto targets of the size we have thus far identified, we decided to suspend further drilling operations until we had explored other possible navigation options.

We accordingly reverted to ROV operations. *Isis* dive 71 commenced at 2345Z, at start point 2°16.0′N 101°33.094′N. It will swath map the area immediately west of that surveyed during dives 67 and 68.

Tuesday 22nd January 2008 (2008/022Z)

On site, Hess Deep. Isis swath dive 71 (ongoing). Local noon fix (GMT-7): 2°15.90′N 101°33.28′W; weather overcast to light rain, wind 12kt from 200°, rolling easily to slight sea and long low northerly swell.

Isis swath operations on dive 71: mowing the lawn in N-S swaths spaced 175m apart, working progressively westwards. A quiet day. Will Handley kindly made 3-D scene files of both the dive 67-68 mosaic and our EM120 Hess Deep data for us using Fledermaus (he has the only copy on board). Copies of the files and free iView viewer were rapidly distributed amongst the science party and have stimulated the first interpretations of the broader picture of our surveying and sampling so far.

Wednesday 23rd January 2008 (2008/023Z)

On site, Hess Deep. Isis swath dive 71 and brief EM120 swath survey of area southwest of Hess Deep during Isis maintenance. Local noon fix (GMT-7): 2°15.81′N 101°33.20′W; weather overcast to heavy rain, wind 8kt from 180°, slight sea and low northeasterly swell.

Isis was able to stay in the water longer substantially longer than predicted, in part because of the shallower water depths in which we operated at the end of the survey. We therefore extended the survey farther west than originally planned – as far west as 101°33.567′W for the final swath – and some across-track tie-lines.

When *Isis* was eventually brought on board it was found that the bearings on both vertical thrusters needed replacing. Because the *Isis* team only had one spare ready to swap in they were required to recondition one there and then: a job taking 3-4 hours or more. We decided to use that downtime to conduct an EM120 ship's swath bathymetry survey (at 4kt) over an area to the southwest of Hess Deep itself, to fill in an area never previously surveyed. This extended as far as 2°08.5′N 101°47.5′W. The shipboard magnetometer was deployed. We curtailed the survey in order to transit back (at 10kt) to the starting point of *Isis* dive 72 at the time the *Isis* group had the ROV ready to go back into the water.

Thursday 24th January 2008 (2008/024Z)

On site, Hess Deep (Isis near-bottom dive 72), and then start of emergency transit to Costa Rica. Local noon fix (GMT-7): 2°29.3′N 101°00.7′W; average speed 13.2kt; distance made good 39.5nm; weather overcast to heavy rain, wind 7kt from 062°, slight sea and low swell.

In the early morning we received the news of the tragic death of a close family member of one of the ship's crew. The Master took the decision that she needed to be put ashore as soon as possible. Science operations were accordingly curtailed immediately, and *Isis* dive 72 was aborted. The ship then headed at 13kt (the greatest speed attainable given the prevailing currents) for Caldera in Costa Rica, which is the closest accessible landfall. At maximum speed we estimate a transit of three days each way. The PSO and the Master discussed plans as to how to minimise the loss of science time. Current estimations are that the remaining time on site, after returning from Costa Rica, could be as little as four days; however, if authorisation is given from Southampton for one or more of the logistical suggestions made, then another couple of days could be found.

Friday 25th January 2008 (2008/025Z)

Emergency transit to Costa Rica. Local noon fix (GMT-7): 4°38.9′N 95°59.9′W; average speed 13.6kt; distance made good 327nm; weather clear and fine, wind light airs, slight sea and low swell.

Confirmation was received from NMF HQ that cruise JC21 could end in Costa Rica rather than Panama on 10th February, and that NERC would pay for the science party to be flown from San José to Panama to pick up their existing flight reservations home on 11th February. Because of the shorter transit this should gain us an extra day or day and a half of science time: hopefully 6-6.5 days overall. Clocks were advanced one hour to GMT-6 in the evening.

Saturday 26th January 2008 (2008/026Z)

Emergency transit to Costa Rica. Local noon fix (GMT-6): 6°38.9′N 91°21.3′W; average speed 13.0kt; distance made good 299nm; weather clear and fine, wind 12kt from 050°, slight sea and low swell.

The science party were variously employed in finishing sample descriptions and continuing to work on cleaning up and processing the ROV swath bathymetry data.

Sunday 27th January 2008 (2008/027Z)

Emergency transit to Costa Rica. Local noon fix (GMT-6): 8°47.5′N 86°21.9′W; average speed 13.4kt; distance made good 322nm; weather clear and fine, wind 10kt from 030°, slight sea and low swell.

Hurrying to meet a rendezvous in the harbour of Puerto Caldera, the ship was coaxed at times up to 15kt as we approached Costa Rica. These speeds could not be maintained for long periods, as with sea temperatures in excess of 25°C the ship's cooling system could not cope with having all four engines in operation for more than a few hours at a time. We were also battling headwinds at times of as much as 30kt. We finally made landfall in Puerto Caldera, in the Gulf of Nicoya (9°55.04′N 84°43.51′W), in early-mid evening, crawling into harbour to meet up with a water taxi in sheltered waters a few hundred metres from the quayside. Replacement catering assistant Graham Mingay came aboard. Negotiations with customs agents took some time and required gifts of ship T-shirts, Quality Street and Fairy Liquid to get through the paperwork. Eventually Amy Whalen and Jacqui Paterson disembarked onto the small boat alongside and set off back to the UK. After a total of three-and-a-half hours in port *James Cook* turned about and set sail again for the three-and-a-half day voyage back to Hess Deep.

Monday 28th January 2008 (2008/028Z)

Transit back to Hess Deep. Local noon fix (GMT-6): 8°26.9′N 87°10.4′W; average speed 13.0kt; distance made good 266nm; weather clear and fine, wind 19kt from 020°, moderate following sea and low swell.

At the daily science meeting Steve Hurst gave a talk on his previous work on the north wall of Hess Deep. The GMTers continued to improve the *Isis* swath data and, with Will Handley's help, generated some more Fledermaus images. These in turn generated further discussion of the broader-scale structure of Hess Deep and debate as to the prioritisation of remaining science time once back on site.

Tuesday 29th January 2008 (2008/029Z)

Transit back to Hess Deep. Local noon fix (GMT-6): 6°18.5′N 92°09.0′W; average speed 13.4kt; distance made good 322nm; weather clear and fine, wind 5kt from 040°, slight sea and low swell.

Progress was made on parts of the cruise report. Some of the science party went on an engine room tour.

Wednesday 30th January 2008 (2008/030Z)

Transit back to Hess Deep. Local noon fix (GMT-6): 4°15.7′N 96°53.2′W; average speed 12.8kt; distance made good 307nm; weather overcast with rain showers, wind 9kt from 250°, moderate sea and low swell.

Headwinds and counter-currents are delaying our progress slightly, and our ETA on site has slipped to the middle of the day tomorrow. Pirate drill was held in the morning, but was not as exciting as it sounds.

Thursday 31st January 2008 (2008/031Z)

Transit back to Hess Deep, arrival on site, then start of Isis near-bottom dive 73 (ongoing). Local noon fix (GMT-6): 2°20.6′N 101°30.3′W; average speed 12.2kt; distance made good 266nm; weather overcast, wind 14kt from 200°, slight sea and low swell.

We finally arrived back on site at lunchtime. Waypoints were fixed such that we filled in a few gaps in the ship multibeam (and surface magnetometer) coverage of the northeastern part of the Hess Deep valley as we approached the launch point of the first *Isis* dive. The starting point of this dive is located between the previous dives 69 and 70.

Friday 1st February 2008 (2008/032Z)

On site, Hess Deep. Isis near-bottom dive 73. Local noon fix (GMT-6): 2°15.4′N 101°33.0′W; weather overcast, clearing later, wind 10kt from 186°, slight sea and low swell.

The entire day was spent with *Isis* on the bottom, sampling wherever possible up the slope from 5200m (~300m below the mid-slope terrace) roughly up longitude 101°32.6′W up to 4600m. After this we contoured westwards and northwards to cover in reconnaissance the NW corner of the SM2000 swath-mapped area and complete the aborted near-bottom dive 72.. The primary aim of the dive was to better constrain the along-contour lithological variations between the dives 69 and 70: specifically to determine whether the NE-trending lineaments that cut obliquely across the slope could be responsible for the difference between the mantle/Moho transition zone lithologies to the east and gabbros to the west. We also spent several hours sampling in detail the gabbro outcrop (At 4750m) from which samples 70R-14 and –15 had previously been collected and which appeared to display (E- to SE-dipping) layering. It proved to be quite a challenge to recover pieces from each layer: on several occasions samples fell from the manipulator claws and plummeted into the abyss. Eventually, though, an additional seven samples were collected from the one outcrop plus another one very close by. This should ultimately give us good constraint on metre-scale lithological and chemical variation in a contiguous section of primitive olivine gabbros deep in the stratigraphic section.

In the evening *Isis* was brought (with difficulty) to deck laden to the gunwales with 27 samples somewhat larger and considerably heavier than our estimates from the on-bottom video. The largest slab weighed 27kg alone, and the total a very healthy 156kg.

Saturday 2nd February 2008 (2008/033Z)

On site, Hess Deep. Isis swath dive 74 on the intra-rift ridge. Local noon fix (GMT-6): 2°17.6'N 101°31.9'W; weather clear and fine, light airs, calm sea and low swell.

Isis was redeployed in swath mode to map the southern slopes of the western part of the intra-rift ridge. The purpose of dive 74 was to obtain detailed bathymetry of the steep slopes to help make our near-bottom sampling of this section as efficient as possible. Because we were interested in an area much broader than it was high, we ran lines E-W along-contour, as opposed to the N-S up- and down-slope strategy employed during our survey of the main lower slope area. This minimised time lost on turns and allowed *Isis* to be flown at constant depth, which is apparently easier on both machine and pilots. The SM2000 automatic depth-picking algorithms seemed to cope better, though the very steep across-track slopes made the swaths on either side of the vehicle very different in width.

A short run on the summit of the intra-rift ridge was also made, covering ODP Site 894 and thus broadening our options with regard to potential IODP drill sites, as the Site Survey Panel require high-resolution bathymetry of proposed sites. Although not targetted specifically in Proposal #551, we recognise that a well-prepared deep hole (~500m+) at Site 894 would be of high scientific value.

An hour was lost early in the dive because the data ceased copying across the ROV network to the RAID drive. It turned out that this happened because someone (well, OK, it was Benoît) was copying video data off the drive at the same time and hogging all the bandwidth of the network and CPU of the RAID drive. Towards the end of the dive the acquisition PC for the USBL logging of the ROV position crashed and about an hour of data (~450-500m of line) were collected without USBL positioning. From the doppler data and the offset when the acoustic navigation was restored we deduced that the drift away from the expected track over this period was <10m, so we did not rerun the line. Fine-tuning using the doppler data can be done post-cruise.

The day was otherwise a relatively quiet one, with much of the description of the dive 73 samples being made. In essence we found that samples 73R-1 to -21 (from the south-to-north traverse) were gabbros, but those from the upper and western parts of the section were all dolerite. A pattern is emerging that suggests the NE-trending features that traverse the swath-mapped area do indeed control the distribution of exposure of the major lithological types. Progressively higher stratigraphic levels occur progressively northwestwards across the southern slope and appear to show that the NE structures have a normal component of displacement down to the NW. This pattern looks to be repeated on a much larger scale across the intra-rift ridge as a whole.

Sunday 3rd February 2008 (2008/034Z)

On site, Hess Deep. Isis near-bottom dive 75 on the intra-rift ridge. Local noon fix (GMT-6): 2°17.00'N 101°32.68'W; weather cloudy to clear and fine, wind 7kt from 150°, calm sea and low swell.

For dive 75, *Isis* was redeployed in near-bottom mode to sample the southern slopes of the intra-rift ridge, the area swath-mapped on dive 74.

It was Masako's birthday, and she was presented with a shoe made out of a plastic bottle and duck tape to replace the one she accidentally kicked overboard at 6°18.5072'N 92°09.0367'W a few days ago.

Monday 4th February 2008 (2008/035Z)

On site, Hess Deep. Isis end of near-bottom dive 75 and start of near-bottom dive 76, both on the intra-rift ridge. Local noon fix (GMT-6): 2°17.37'N 101°32.15'W; weather cloudy to clear and fine, wind 14kt from 180°, slight sea and low swell.

Near-bottom dive 75 worked up the slope of the intra-rift ridge from 2°17.0'N (4200m) up to 2°17.75'N (3200m), over the western part of our intra-rift ridge swath survey. Much of the ascent followed one of the NE-trending lineaments identified across the whole JC21 survey area. This NE fault scarp is clearly active or recently so. It steps down to the SE and is either vertical or overhanging for as far as we could trace it, suggesting it might have a reverse (or reverse component of) motion. It clearly post-dates the E-W south-dipping faults that are otherwise pervasive on the southern intra-rift ridge slope, and allowed us to sample a coherent section of continuous outcrop for more than a hundred metres upslope. The E-W fault surfaces dip steeply southward (at an estimated 60-70°), parallel to the prominent fracture set visible throughout the ODP Hole 894G cores and borehole images.

Tuesday 5th February 2008 (2008/036Z)

On site, Hess Deep. End of Isis near-bottom dive 76, and dive 77, intra-rift ridge. Local noon fix (GMT-6): 2°17.25'N 101°29.62'W; weather overcast with rain showers, wind 14kt from 180°, slight sea and low swell.

Isis dive 76 worked up the eastern side of the intra-rift ridge swath-mapped area, ending up on the top of the intra-rift ridge at or near ODP Site 894. Some scattered debris from the ODP operations was seen, but we were unable to spot the Hole 894G hard-rock guidebase in its quoted position. Fifteen samples, totalling some 116kg, were collected on this dive. They appear to provide us with fresher material from the uppermost slopes of the intra-rift ridge south face than we recovered on dive 75: of which many were cataclastic and highly altered.

Dive 77 was sited on the narrow central saddle of the intra-rift ridge, carefully located so as to characterise what we believe to be the central of the three NE-fault-bounded lozenges that constitutes the intra-rift ridge. It was the first time we had ventured in near-bottom (sampling) mode without having first done an *Isis* swath over the area. No major problems were encountered in this. We recovered fourteen samples (115kg total) from here, of peridotite and dolerite.

Wednesday 6th February 2008 (2008/037Z)

On site, Hess Deep (Isis near-bottom dive 78, intra-rift ridge), then start of transit to Costa Rica with brief ship swath survey upon departure from site. Local noon fix (GMT-6): 2°18.2'N 101°32.0'W; weather varying from overcast with heavy rain showers to sunny, wind 6kt from 105°, slight sea and low swell.

Antonio the Master had given us a deadline of 2pm local time (037/2000Z) for leaving the survey area and heading for home. Being disciplined with our timings on dive 77 and with a very quick turnaround of *Isis* on deck at the end of it there was time for one quick final dive with approximately eight hours on bottom. Although we were attracted by the possibility of resampling the continuous outcrop along the NE fault from the lower intra-rift section, ultimately we thought the highest priority would be to sample the northern part of the intra-rift ridge to see if we could recover material stratigraphically higher than the section drilled at ODP Hole 894G. Ultimately we took 18 samples, totalling 111kg, of gabbro and dolerite. For the cruise as a whole the total weight of samples collected using *Isis* was 760kg.

Thursday 7th February 2008 (2008/038Z)

Transit to Costa Rica. Local noon fix (GMT-6): 3°56.9′N 97°21.2′W; average speed 14.5kt; distance travelled 220nm; weather overcast to clear, wind light airs, slight sea and low swell.

The day was spent by the science party in working on curating and describing the dive samples, and writing and collating material for the cruise report. The formal cruise debrief meeting chaired by the Master occupied Chris, Damon and Donna for half of the day. In the evening a semi-formal dinner was held for all, preceded (and, for some, followed) by drinks in the bar. Damon viewed both sunset and sunrise from the same seat in the bar.

Friday 8th February 2008 (2008/039Z)

Transit to Costa Rica. Local noon fix (GMT-6): 6°09.7′N 92°19.8′W; average speed 13.7kt; distance travelled 328nm; weather clear and fine, wind light airs, slight sea and low swell.

More hard work for the science party in collating information for the cruise report and packing up. In the evening a barbecue was held on the starboard main deck.

Saturday 9th February 2008 (2008/040Z)

Transit to Costa Rica. Local noon fix (GMT-6): 8°20.6′N 87°22.1′W; average speed 13.5kt; distance travelled 324nm; weather fine and clear, wind 10kt from 050°, slight sea and low swell.

Logging of the ship's EM120 multibeam sonar was switched off in the morning as we entered Costa Rican territorial waters. Final compilation and distribution of the cruise report; packing of crates and boxes either to be airfreighted home or left on board ship until its return to the UK in June. A science meeting was held in the afternoon to discuss post-cruise science plans.

Sunday 10th February 2008 (2008/041Z)

Arrival in Puerto Caldera, Costa Rica, 9°55′N 84°43.8′W. End of cruise JC21.

Arrival in Puerto Caldera, Gulf of Nicoya, Costa Rica. The science party disembarked by boat transfer and were taken to San José. Because the cruise was originally to have ended in Panama, everyone had flights departing from there. Those with flights early on the morning of 11th flew direct from San José on 10th, staying overnight in Panama; those with flights later on 11th stayed in San José overnight and flew on to Panama that morning.

Chapter 7. End Matter

7.1 References

Allerton, S., Wallis, D., Derrick, J., Smith, D. & MacLeod, C.J., New wireline seafloor drill augers well. Eos Trans. AGU., 80 (33), 367, 1999.

Ballu, V., Hildebrand, J.A. and Canuteson, E.L., 1999. The density structure associated with oceanic crustal rifting at the Hess Deep: a seafloor and sea-surface gravity study. Earth and Planetary Science Letters, 171(1): 21-34.

Blackman, D.K., Ildefonse, B., John, B.E., Ohara, Y., Miller, D.J., MacLeod, C.J., and the Expedition 304/305 Scientists, 2006. Proc. IODP, 304/305: College Station TX (Integrated Ocean Drilling Program Management International, Inc.). doi:10.2204/iodp.proc.304305.2006

Boudier, F., Nicolas, A. and Ildefonse, B., 1996. Magma chambers in the Oman ophiolite : fed from the top or from the bottom ? Earth and Planetary Science Letters, 144: 239-250.

Coogan, L.A., Gillis, K.M., MacLeod, C.J., Thompson, G.,, Hekinian, R., 2002. Petrology and geochemistry of the lower, ocean crust formed at the East Pacific Rise and exposed at Hess Deep: a synthesis and new results. Geochem. Geophys. Geosyst. Special issue: The Oman ophiolite and ocean ridge processes. DOI:10.1029/2001GC000230.

Francheteau, J., Armijo, R., Cheminee, J.L., Hekinian, R., Lonsdale, P., Blum, N., 1990. 1 Ma East Pacific Rise oceanic crust and uppermost mantle exposed by rifting in Hess Deep (equatorial Pacific Ocean). Earth Planet. Sci. Lett. 101, 281–295.

Gillis, K.M., Mével, C., Allan, J. (Eds.), 1993. Proc. ODP, Init. Repts., vol. 147. Ocean Drilling Program, College Station, TX. 366 pp.

Henstock, T.J., Woods, A.W. and White, R.S., 1993. The accretion of oceanic crust by episodic sill intrusion. Journal of Geophysical Research, 98(B3): 4143-4161.

Karson, J.A., Klein, E.M., Hurst, S.D., Lee, C.E., Rivizzigno, P.A., Curewitz, D., Morris, A.R., Miller, D.J., Varga, R.G., Christeson, G.L., Cushman, B., O'Neill, J.M., Brophy, J.G., Gillis, K.M., Stewart, M.A. and Sutton, A.L., 2002. Structure of uppermost fast-spread oceanic crust exposed at the Hess Deep Rift: Implications for subaxial processes at the East Pacific Rise. Geochemistry Geophysics Geosystems, 3.

Kelemen, P., Koga, K. and Shimizu, N., 1997. Geochemistry of gabbro sills in the crust-mantle transition zone of the Oman ophiolite: implications for the origin of the oceanic lower crust. Earth and Planetary Science Letters, 146: 475-488.

Klein, E. M., Smith, D. K., Williams, C. M. and Schouten, H., 2005. Counter-rotating microplates at the Galapagos triple junction. Nature, 433: 855-858.

Lonsdale, P., 1988. Structural Pattern of the Galapagos Microplate and Evolution of the Galapagos Triple Junctions. Journal of Geophysical Research-Solid Earth and Planets, 93(B11): 13551-13574.

MacLeod, C.J. and Yaouancq, G., 2000. A fossil melt lens in the Oman ophiolite: Implications for magma chamber processes at fast spreading ridges. Earth and Planetary Science Letters, 176(3-4): 357-373.

MacLeod, C.J., Boudier, F., Yaouancq, G. and Richter, C., 1996a. gabbro fabrics from Site 894, Hess Deep : implications for magma chamber processes at the East Pacific Rise. In: C. Mével, K.M. Gillis, J.F. Allan and P.S. Meyer (Editors), Proc. ODP, Sci. Res. Ocean Drilling Program, College Station, TX,147, pp. 317-328.

MacLeod, C.J., Célérier, B., Früh-Green, G.L. and Manning, C.E., 1996b. Tectonics of Hess Deep: A synthesis of drilling results from Leg 147. In: C. Mével, K.M. Gillis, J.F. Allan and P.S. Meyer (Editors), Proc. ODP, Sci. Res. Ocean Drilling Program, College Station, TX, 147, pp. 461-475.

Phipps Morgan, J. and Chen, Y.J., 1993. The genesis of oceanic crust : magma injection, hydrothermal circulation, and crustal flow. Journal of Geophysical Research, 98(B4): 6283-6297.

Quick, J.E. and Denlinger, R.P., 1993. Ductile deformation and the origin of layered gabbro in ophiolites. Journal of Geophysical Research, 98(B8): 14015-14027.

Sinton, J.M. and Detrick, R.S., 1992. Mid-ocean ridge magma chambers. Journal of Geophysical Research, 97(B1): 197-216.

Streckheisen, A., 1974. Classification and nomenclature of plutonic rocks. *Geol. Rundsch.,* 63: 773–786.

Wiggins, S.M., Dorman, L.R.M., Cornuelle, B.D. and Hildebrand, J.A., 1996. Hess Deep rift valley structure from seismic tomography. Journal of Geophysical Research - Solid Earth, 101(B10): 22335-22353.

Wilson, D.S., Teagle, D.A.H., Alt, J.C., Banerjee, N.R., Umino, S., Miyashita, S., Acton, G.D., Anma, R., Barr, S.R., Belghoul, A., Carlut, J., Christie, D.M., Coggon, R.M., Cooper, K.M., Cordier, C., Crispini, L., Durand, S.R., Einaudi, F., Galli, L., Gao, Y.J., Geldmacher, J., Gilbert, L.A., Hayman, N.W., Herrero-Bervera, E., Hirano, N., Holter, S., Ingle, S., Jiang, S.J., Kalberkamp, U., Kerneklian, M., Koepke, J., Laverne, C., Vasquez, H.L.L., Maclennan, J., Morgan, S., Neo, N., Nichols, H.J., Park, S.H., Reichow, M.K., Sakuyama, T., Sano, T., Sandwell, R., Scheibner, B., Smith-Duque, C.E., Swift, S.A., Tartarotti, P., Tikku, A.A., Tominaga, M., Veloso, E.A., Yamasaki, T., Yamazaki, S. and Ziegler, C., 2006. Drilling to gabbro in intact ocean crust. Science, 312(5776): 1016-1020.

7.2 Acknowledgements

We gratefully acknowledge funding for this cruise by the Natural Environment Research Council through the Site Survey Initiative of the UK IODP programme. We thank Professor Sir Geoffrey Allen FRS, Professor Mike Bickle FRS, and Dr Chris Franklin and other NERC staff for their support over the years it has taken for this project to come to fruition. Colin Day of NMF SS provided much useful advice throughout the planning of the cruise.

We owe the success of the cruise in large part to the unstinting efforts and professionalism of Captain Antonio Gatti, the officers and crew of RRS *James Cook.* Although nature did not cooperate, the BGS group gave us support throughout. Dave Turner and the *Isis* team, from the National Oceanography Centre, Southampton, performed superbly under great pressure for the duration of the cruise and their contribution cannot be overstated. We thank you all.

7.3 A note on the citation of this report

The appendices listed below contain much of the detailed, specific information collected during the cruise. Because this information will form the basis for the post-cruise research of the entire academic science party, including the primary material for two PhD studentships, we consider this to be proprietary for the duration of the project. Accordingly, we do not distribute the appendices with the cruise report except to the JC21 scientific party. Any enquiries or requests in this regard should be directed to the Principal Scientist, Dr. Chris MacLeod, at Cardiff University (macleod@cardiff.ac.uk).

For the same reason, this cruise report should be cited only in the context of its operations rather than for academic purposes, except with the express permission of the Principal Scientist. In such cases it should be cited as follows:

MacLeod, C.J., Teagle, D.A.H., Gillis, K.M., Cazenave, P.W., Hansen, H.E., Harris, M., Hurst, S.D., Ildefonse, B., Lissenberg, C.J., Morris, A., Shillington, D.J. & Tominaga, M., 2008. *Accretion of the lower oceanic crust at fast-spreading ridges: a rock drill and near-bottom seafloor survey in support of IODP drilling in Hess Deep.* RRS *James Cook* JC21 Cruise Report, Cardiff University, 50pp.

7.4 List of Appendices

A01_Science_operations_log

An Excel workbook containing the watchkeepers science operations log for JC21

A02_Magnetometer_operations

Provides a technical description of the acquisition and processing of near-bottom magnetometer data during Isis operations

A03_Swath_bathymetry

Contains descriptions of the acquisition and processing of ship-mounted EM120 and Isis-mounted MS2000 swath bathymetry data, and associated issues. A comprehensive suite of bathymetric images are provided, both at the regional scale (EM120 operations) and detailed scale (MS2000 operations). Also includes Fledermaus scenes derived from the bathymetric data collected during JC21, and Illustrator files containing bathymetric and sample location data arranged in layers.

A04_Isis_dive_navigation_data

A suite of contoured bathymetry maps showing the Isis dive tracks, together with data files of timestamped positions and depths for each dive.

A05_ISIS_Event_Log&Images

Contains an Excel workbook of the event log for the Isis dives, updated to include timestamped information on image acquisition, together with folders of digital still images captured during dive operations.

A06_Ship+Drill+ROV_System_reports

A series of documents provided by the Isis ROV and BRIDGE drill teams containing relevant technical information on the ship, Isis and BRIDGE drill systems.

A07_Sample_Location_Images

Contains digital imagery of the Isis ROV and BRIDGE drill sampling sites.

A08_Sample_log_sheets

Summary PDF documents describing the samples collected during JC21.

A09_Petrology_summaries

Contains Excel workbooks containing shipboard petrological data for the JC21 sample collection.

A10_Sample_Photographs

Provides digital still images of all sample collected during JC21, including photographs of cut surfaces.